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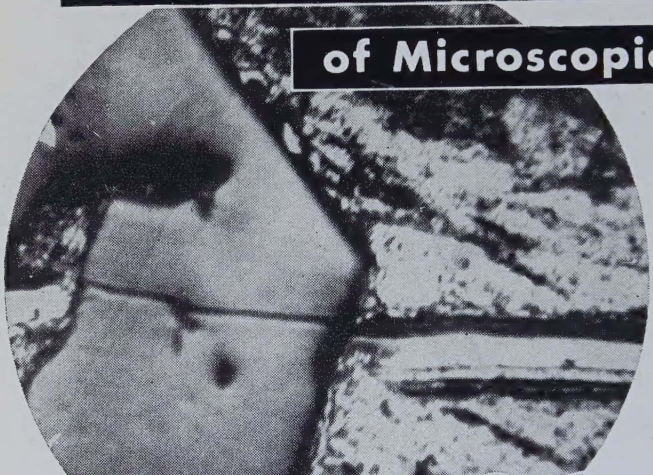

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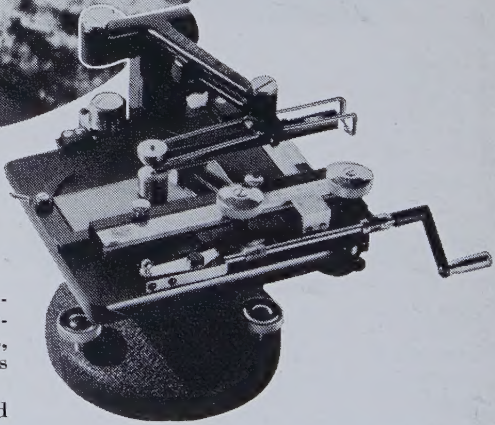

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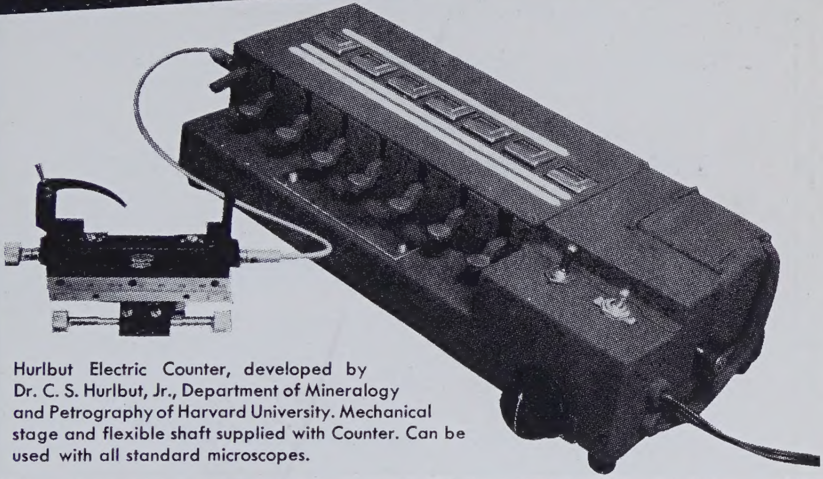

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JOURNAL OF THE MINERALOGICAL SOCIETY OF AMERICA

Vol. 33 JANUARY–FEBRUARY, 1948 Nos. 1 and 2

TOURMALINE PRESSURE GAUGES*

CLIFFORD FRONDEL, *Harvard University,*
Cambridge, Massachusetts.

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ABSTRACT

Large single-crystals of tourmaline have been in demand in recent years for use in piezoelectric gauges for the measurement of blast pressures in air and under water. Tourmaline is responsive piezoelectrically to hydrostatic pressure and because of this and its high mechanical strength and chemical stability is used in preference to quartz and various water-soluble salts such as ADP and Rochelle-salt. The gauges comprise thin discs of tourmaline from $\frac{1}{4}$ inch up to several inches in diameter cut perpendicular to the *c*-axis and used singly or in stacks. The design and construction of the gauges is described in detail. The piezoelectric response of the tourmaline is amplified and recorded on associated electronic equipment and both the magnitude of the peak pressure and the wave-form deduced thereby.

The sources of supply, price and factors determining the usability of raw tourmaline for the purpose are discussed. Tourmaline for radio oscillator-plates must be entirely free from imperfections, and requires crystals of gem quality, but material for gauges can contain a considerable amount of cracking. The size and shape of the raw crystals are added factors in grading, but the color (composition) is of no consequence. Most of the tourmaline employed is of low-iron, high-alkali types from Madagascar and Brazil.

TOURMALINE PRESSURE GAUGES

During recent years, tourmaline has found an important application in the construction of piezoelectric gauges for the measurement of blast pressures in air and in sea-water. The present paper describes the design of tourmaline gauges and the relevant properties of the mineral but is primarily concerned with the specification and processing of raw tourmaline for the purpose.

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* Contribution from the Department of Mineralogy and Petrography, Harvard University, No. 290.

FIELD OF APPLICATION OF PIEZOELECTRIC GAUGES

The basic problem in the study of shock-waves emanating from an explosion is the resolution of the wave-form, or pressure versus time curve, the principal points of interest being the shape of the wave-front and the magnitude of the peak pressure. The circumstances of measurement are ordinarily such that the incident pressures range up to a few hundred pounds per square inch in air and from a few thousand up to 30,000 psi or so in water measurements, although much higher pressures have been explored. The time interval over which the transient pressure wave is significant ranges from a few microseconds up to several hundred milliseconds. These conditions impose severe limitations on the type of gauge to be employed. Mechanical gauges, such as the ball-crusher type, are incapable of resolving the pressure-time curve, and are suited only to the measurement of peak pressure at relatively high pressure levels. Electromechanical devices, in which an applied pressure generates an electrical charge, in turn amplified and recorded, are better suited to the purpose primarily because of the continuous and nearly instantaneous nature of the response. In the condenser type of gauge, the applied pressure changes the capacitance of the condenser by effecting a mechanical displacement of the electrode plates. The so-called resistance gauges utilize materials that have a high pressure or strain coefficient of electrical resistance. Electromagnetic and magnetostrictive devices also have been developed for the purpose. Devices of the types mentioned are somewhat objectionable, variously because of non-linearity of response, low signal intensity or lack of ruggedness, and most of the work in recent years has been concerned with the development of gauges similar in principle but utilizing piezoelectric single-crystals.

The interconversion of electrical and mechanical energy effected by certain kinds of crystals immediately suggests their application to the measurement of pressure. Shortly after Pierre and Jacques Curie discovered the phenomenon of piezoelectricity in 1880, the two brothers devised a *manomètre piëzoëlectrique* that was a forerunner of the gauges described beyond. Their instrument[1] comprised a quartz plate cut perpendicular to a piezoelectric $X=a$-axis with attached electrodes connect-

[1] Curie, P., Oeuvres de Pierre Curie, Paris (**1908**, p. 38); *Jour. de Phys.*, [2] **8,** 149 (1889).

ing with an electrometer. Pressure applied in the direction of the X axis caused a deflection of the electrometer proportional to the applied force. Various adaptations of this gauge were later applied by others to the measurement of cylinder pressures in internal combustion engines, explosive pressures in firearms and artillery, blood pressures in veins and arteries and varied other problems.

TABLE 1. TYPES OF PIEZOELECTRIC RESPONSE AMONG THE 32 CRYSTAL CLASSES

Class Number	System	Class Name	Hermann-Mauguin Symbol	Piezo-electric	Hydrostatically Sensitive	Not Hydrostatically Sensitive
1	Triclinic	Pedial	1	*	*	
2	"	Pinacoidal	$\bar{1}$			
3	Monoclinic	Domatic	m	*	*	
4	"	Sphenoidal	2	*	*	
5	"	Prismatic	$2/m$			
6	Orthorhombic	Rhombic-pyramidal	$mm2$	*	*	
7	"	Rhombic-disphenoidal	222	*		*
8	"	Rhombic-pyramidal	$2/m\,2/m\,2/m$			
9	Tetragonal	Tetragonal-disphenoidal	$\bar{4}$	*		*
10	"	Tetragonal-pyramidal	4	*	*	
11	"	Tetragonal-dipyramidal	$4/m$			
12	"	Tetragonal-scalenohedral	$\bar{4}2m$	*		*
13	"	Ditetragonal-pyramidal	$4mm$	*	*	
14	"	Tetragonal-trapezohedral	422	*		*
15	"	Ditetragonal-dipyramidal	$4/m\,2/m\,2/m$			
16	Hexagonal-P, R	Trigonal-pyramidal	3	*	*	
17	"	Rhombohedral	$\bar{3}$			
18	"	Ditrigonal-pyramidal	$3m$	*	*	
19	"	Trigonal-trapezohedral	32	*		*
20	"	Hexagonal-scalenohedral	$\bar{3}\,2/m$			
21	Hexagonal-P	Trigonal-dipyramidal	$\bar{6}$	*		*
22	"	Hexagonal-pyramidal	6	*	*	
23	"	Hexagonal-dipyramidal	$6/m$			
24	"	Ditrigonal-dipyramidal	$\bar{6}m2$	*		*
25	"	Dihexagonal-pyramidal	$6mm$	*	*	
26	"	Hexagonal-trapezohedral	622	*		*
27	"	Dihexagonal-dipyramidal	$6/m\,2/m\,2/m$			
28	Isometric	Tetartoidal	23	*		*
29	"	Diploidal	$2/m\,\bar{3}$			
30	"	Hextetrahedral	$\bar{4}3m$	*		*
31	"	Gyroidal	432			
32	"	Hexoctahedral	$4/m\,\bar{3}\,2/m$			

It must be noted that in every piezoelectric substance, except those belonging to the triclinic pedial class, that the crystal plate must be properly oriented in order to obtain a response, and that in some substances the pressure must be properly applied as well. Thus 20 of the 32 crystal classes permit the occurrence of piezoelectricity. In 10 of these classes a piezoelectric response is obtained only if the pressure is applied in certain directions, while in the 10 remaining classes a response is obtained from hydrostatic compression as well. The crystal classes responsive in these ways are indicated in Table 1. Substances in the nonhydrostatically sensitive classes, which include quartz, when used for the measurement of hydrostatic pressures require holders or gauge-bodies which laterally shield the crystal and transmit the applied force by means of a piston to only one face of the crystal plate.

The problem of gauge design is simplified considerably by employing a hydrostatically sensitive substance. It is also desirable that the substance have a high mechanical strength, since it may be subjected to pressures ranging up to many tons per square inch, and that it is insoluble in water and not hygroscopic. Chemical and structural stability over a wide range of temperature also is a desirable feature, partly because of metal plating and soldering techniques used in the assembly operations. A high piezoelectric response also is advantageous because it eases the problem of amplifying the signal or permits a reduction in the size of the gauge. The temperature coefficient of frequency and the frequency-thickness constant are unimportant, but a large pyroelectric response is undesirable. Generally speaking, the artificial piezoelectric substances so far developed are unsuitable, principally because they are water soluble and mechanically weak, although Rochelle-salt, ammonium dihydrogen phosphate (ADP), lithium sulfate monohydrate and certain tartrates have had a limited application. Tourmaline is now in general use for gauge applications, primarily because it is hydrostatically sensitive, mechanically strong and chemically stable. The piezoelectric response of the substance is comparable to that of quartz but is only about a hundredth of that of Rochelle-salt. The principal drawback to tourmaline is the high cost of crystals of suitable size and quality. But for this, tourmaline probably would have a much wider application in piezoelectric devices, especially for supersonic applications, than it presently enjoys. A search among natural piezoelectric substances with desirable properties, however, has not yielded any practical substitute for either quartz or tourmaline for these applications. Some of the more likely or interesting possibilities that have been investigated in this laboratory are pyromorphite, mimetite, heulandite, stibiotantalite-stibiocolumbite, nepheline, boracite, wurtzite, and hemimorphite.

DESIGN OF PIEZOELECTRIC GAUGES

The details of the design of piezoelectric gauges vary considerably with the particular application, especially in the type of housing employed. Basically, all such gauges consist of one or more plates or discs cut from a properly oriented single-crystal. The surfaces of the disc ordinarily are metal-plated and lead wires are attached thereto. The gauge-element is then housed in an appropriate holder which may be water-proofed and electrically shielded. The piezoelectric response of the gauge-element to the transient pressure wave is transmitted via cable to associated amplifying and recording equipment.[2] The size of the plates or discs employed is fixed primarily by the piezoelectric constants of the material, the magnitude of the pressure changes to be measured, and the requirements of the amplifying equipment. An added factor is the transit time of any given element of the shock wave across the gauge relative to the duration of the wave. The smaller the transit time, and hence the smaller the gauge, the more accurate is the representation of the wave form. The charge produced by a gauge is directly proportional to the surface area of the tourmaline disc and is independent of the thickness of the disc. If a large surface area is needed in order to give an adequate signal under a certain set of conditions it is conventional practice, if single-crystals of sufficiently large size are not available, to employ a stack of small, thin discs attached together so that they are electrically parallel (and crystallographically opposite). Relatively large discs are needed especially in the case of air blast gauges in which the relatively

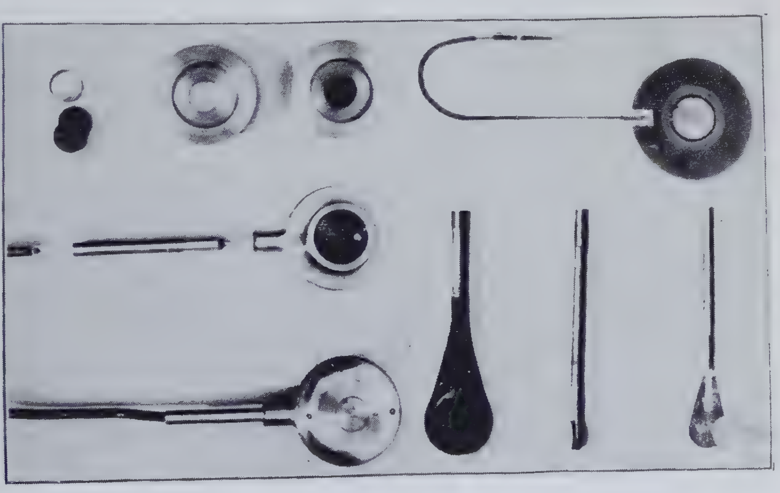

FIG. 1. *Left:* Piston-type air-blast gauge for use with quartz discs. *Right, above:* Air-blast gauge utilizing stacked tourmaline discs; shown without insulation. *Right, below:* Early type of underwater gauge using stacked discs soldered to a supporting metal tab.

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[2] The general problem of the recording and interpretation of blast pressure measurements by the piezoelectric method is described in detail by Arons and Cole: *NDRC Rpt.* No. **A-361,** March (1946).

low incident pressures, usually only a few psi, must be compensated by increased surface area. Mosaic gauge-elements also have been employed, particularly in quartz and ADP underwater signaling devices. Stacking techniques are restricted insofar as a low ratio of width to thickness of the gauge-element is desirable in order to minimize the Bernoulli effect and turbulence as the pressure wave passes the gauge.

The tourmaline discs currently used in air-blast gauges range from an inch or so up to about 2 inches in diameter, although much larger plates, usually as irregular slabs cut directly from the raw crystal, have been employed. Underwater gauges in general employ discs from $\frac{1}{4}$ to $1\frac{1}{4}$ inches in diameter, although four-pile gauges as small as 1/16 inch in diameter have been constructed. Some representative types of gauges used in air-blast and underwater measurements are shown in Fig. 1.

Some Relevant Properties of Tourmaline

Tourmaline crystallizes in the ditrigonal class ($3\,m$) of the rhombohedral system. The space group[3] is $R\,3\,m$. The axial ratio obtained from morphological measurements[4] is $a:c=1:0.4477$, $\alpha=113°57\frac{1}{2}'$, in the orientation and unit of the structural cell.[3] The morphological unit and the unit cell dimensions vary measurably as the chemical composition varies, as noted beyond, and the value given is close to the average of the observed range. Some crystals of typical habit are shown in Fig. 2. The orientation of the discs cut therefrom for gauge applications and the connection between the morphology and the principal electrical and physical properties are shown in Fig. 3.

The principal crystallographic problems for the technician engaged in cutting tourmaline discs and assembling them into gauges are the recognition of the piezoelectric axes of reference, X, Y and Z, specifically the Z-axis, and the separate identification of the ends of the polar Z-axis. The crystallographic and piezoelectric axes are so related that $Z=c$, $X=a$ and Y is perpendicular to the ZX plane and hence in a vertical plane of symmetry (see Fig. 3). The Z axis is the polar, piezoelectric, axis and the plates or discs are cut perpendicular thereto. Z can be recognized in faced crystals by a three-fold distribution of faces when the crystal is viewed along Z (see the upper and lower projections in Fig. 2, in which Z is perpendicular to the paper). Further, the crystals are ordinarily (but not always) more or less elongated parallel to Z, and the side or prism faces are always striated parallel thereto. Z can be located approxi-

---

[3] Buerger and Parrish: *Am. Mineral.*, **22,** 1139 (1937), on an Etta Mine, South Dakota, crystal with $a_0=15.928$, $c_0=7.151$ Å in the hexagonal unit.

[4] From an unpublished critical curvey of the morphology of tourmaline by J. D. H. Donnay (priv. comm., 1947).

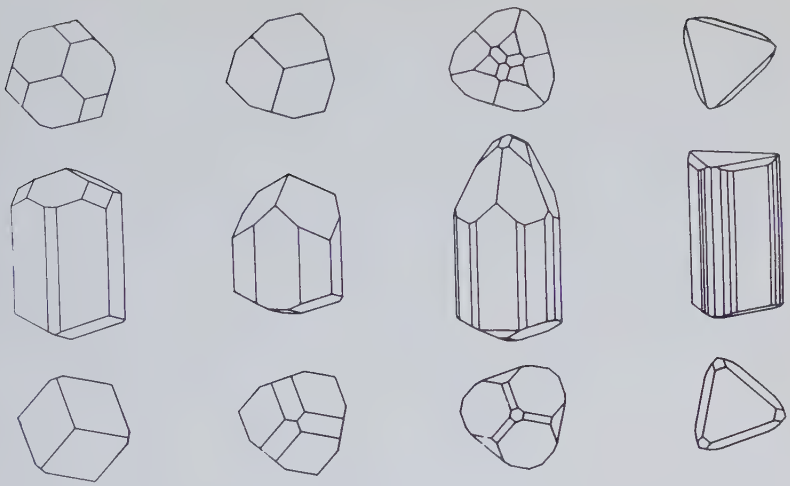

FIG. 2. Some typical habits of tourmaline crystals. Basal projections are given of the antilogous (above) and analogous (below) poles.

mately in unfaced crystals by the electrical tests described beyond; and precisely, provided that the crystal or section is transparent, by viewing the crystal or section in a conoscope or polarizing microscope and locating the optic axis, coincident with *Z*.

The opposite ends of the polar *Z* axis can be identified with certainty only by electrical tests, the antilogous pole—conventionally shown upper-

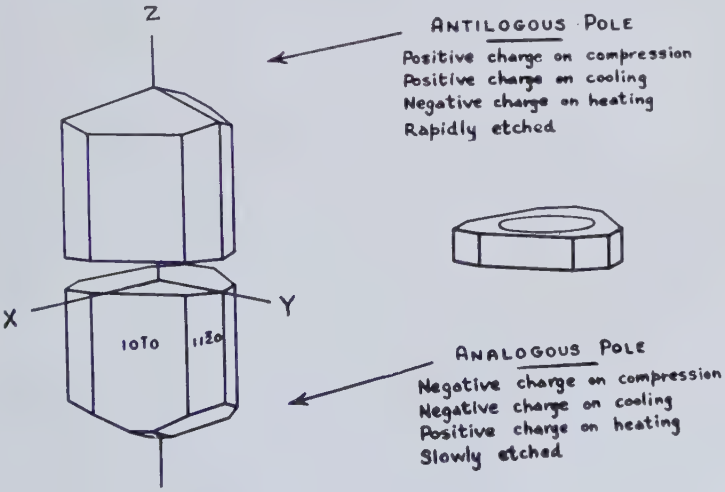
Z
ANTILOGOUS POLE
Positive charge on compression
Positive charge on cooling
Negative charge on heating
Rapidly etched
X
Y
10$\bar{1}$0
11$\bar{2}$0
ANALOGOUS POLE
Negative charge on compression
Negative charge on cooling
Positive charge on heating
Slowly etched

FIG. 3. Correlation between the principal physical and electrical properties of tourmaline and the morphology.

most in crystal drawings—developing a positive electrostatic charge on decrease of temperature or on compression. The opposite, or analogous, pole develops an equal negative charge under the same conditions. A quick and certain electrical method to identify the positive and negative surfaces of sawn slabs and discs is to place the piece in firm contact between two metal plates, one plate being connected to the input post of a sensitive cathode-ray oscilloscope such as the DuMont 208. The other plate is grounded. The horizontal sweep is then synchronized at about 60 cycles/sec. A gentle tapping of the upper plate produces a superimposed signal whose inclination reveals the polarity of the upper surface (input side) of the disc (see Fig. 4). Turning the plate over reverses the signal. In testing for piezoelectricity by this method care must be taken to distinguish effects due to contact potentials and frictional electricity. The polarity also can be determined with a piezometer, in which the voltage produced by squeezing the disc under a small lever arm is impressed on the grid of a high gain amplifier tube such as the 6*J*7. A negative charge impressed on the grid will decrease, and a positive charge increase, the plate current. A milliameter in the plate circuit of the tube permits visual observation of the polarity. Thin discs or fragile materials are not best tested by this method.

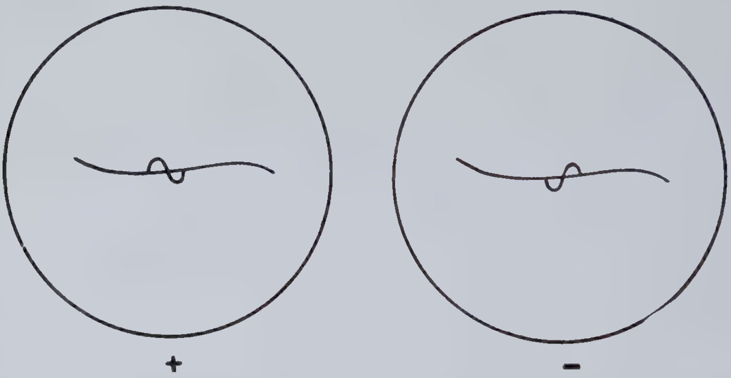

Fig. 4. The drawings represent the screen of a cathode-ray oscilloscope, and show the nature of the superposed signal produced when the antilogous (positive) or analogous (negative) surfaces of the test piece are connected with the input post, and are compressed.

The polar nature of the $Z=c$-axis is well illustrated by differences in the rate of solution and the rate of growth therein. Spheres of tourmaline when dissolved in a solvent develop a bee-hive shape due to a relatively large rate of solution along Z *toward* the analogous pole.[5] Similarly, when sawn Z-cut slabs are etched in a solvent, such as fused KOH containing 5 or 10 per cent H_2O, the surface at the antilogous pole is very much more deeply attacked than the opposite, parallel surface. Etching tests may usefully serve to identify the two poles, but are destructive of the test piece. Study of the color bands within single-crystals often reveals a relatively large rate of growth along Z in the direction toward the antilogous pole,[6] and the secondary overgrowths on rounded detrital grains of tourmaline always are located on the antilogous pole only.[7]

---

[5] Kulaszewski, *Akad. Wiss. Leipzig, Sitzber.*, **72,** 48 (1920); and Frondel, *Am. Mineral.*, **20,** 855 (1935).

As shown in the figures, the opposite ends of the $Z=c$-axis of individual crystals are always or probably always terminated by geometrically different faces or combinations of faces. There are no trustworthy morphological criteria, however, by which the separate poles can be recognized. Several observers have proposed such rules but a recent study[8] has shown that while they may apply to crystals from a particular locality or type of occurrence they are not true in general.

Chemically, tourmaline is a complex borosilicate conforming to the general formula $XY_3ZB_3Si_6O_{27}(O,OH,F)_4$. In this formula, X is Na or Ca with both usually present and Na dominant; Z is Al with some Fe^3 usually present, especially in black tourmaline; Y is one or more of the following: Mg, Fe^2, Fe^3, Al, Li, Mn, Cr; with Mg dominant in the brown tourmaline from crystalline limestones; Fe^2 and Fe^3 present especially in black, pegmatitic tourmaline; Li often present, especially in the light colored varieties. The precise mechanisms by which these varied isomorphous substitutions are effected, particularly those requiring coupled valence compensations, are not clearly understood. The optical properties, specific gravity, color, cell dimensions and other characters of the mineral vary concomitantly with variation in composition. The color banding commonly seen in sawn sections of tourmaline (see Fig. 7) reflects changes in the chemical composition of the crystallizing solution during the growth of the crystal.

Variation in the composition of tourmaline is of interest in the present connection because of the presumed accompanying variation in the piezoelectric properties. The property of interest in gauge construction is the amount of electrostatic charge developed per unit area of a Z-cut plate per unit change of pressure. Determinations of this constant, designated K, and representing averaged measurements of numerous tourmaline discs regardless of their composition, have been made as follows:

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[6] Frondel, *Am. Mineral.*, **21,** 782 (1936).

[7] Krynine, *Jour. Geol.*, **54,** 65 (1946).

[8] J. D. H. Donnay (priv. comm., 1947). The common forms at the antilogous pole are $o\{02\bar{2}1\}$, $r\{10\bar{1}1\}$, $u\{3251\}$, $y\{40\bar{4}1\}$ and $x\{12\bar{3}1\}$; at the analogous pole $\bar{r}\{10\bar{1}1\}$, $\bar{c}\{0112\}$, $\bar{o}\{02\bar{2}1\}$ and $\bar{c}\{0001\}$. Very broadly, the forms at the antilogous pole tend to be more numerous and steeper than those at the analogous pole. Also, $\bar{c}\{000\bar{1}\}$ (analogous) is generally large and dull, while $c\{0001\}$ (antilogous) is small and brilliant and often absent. Striations on $r\{10\bar{1}1\}$ run parallel the opposing edge (or edge between r and o: the short face diagonal); but $\bar{r}\{10\bar{1}1\}$ is always striated parallel the adjacent edges (or edge between $\bar{r}$ and $\bar{e}$).

K = 10.9 micromicrocoulombs per lb. per sq. in. (on *ca.* 100 four-pile airblast gauges[2])
= 11.08 micromicrocoulombs per lb. per sq. in. (on 8 four-pile underwater gauges[2])
= 10.8 micromicrocoulombs per lb. per sq. in. (on 45 four-pile underwater gauges[9])

Numerous determinations on individual discs also have been reported.[2] These show a wide variation, but unfortunately in no case has the chemical composition of the tourmaline been stated so that the significance of the variation is unknown. From a study now in progress, the ordinary range of variation in K in commercially available tourmaline, including both pale colored and black opaque varieties, appears to be about 4 per cent.

The elastic properties of tourmaline have been summed up by Cady.[10]

SPECIFICATIONS OF RAW TOURMALINE

Size and Shape of Raw Crystals

SIZE. The range of sizes of raw tourmaline needed for gauges and most other electronic applications is from 1 to 4 inches as measured in the minimum dimension at right angles to the $Z = c$-axis. Only rarely are crystals needed in sizes up to 6 or 7 inches in diameter. The length of the crystal along the Z axis is not critical, but in small sizes at least the length should not be less than the diameter and in general the longer the crystal the better. If raw tourmaline was abundant and cheap, so that a selection of material could be effected, it would be desirable to use only the largest sizes available. This is true because of cracks and other defects invariably present in the material which cause a relatively small yield of large discs, so that the supply of these usually is inadequate. In large crystals a considerable amount of trim material becomes available which can be salvaged for discs of a range of smaller sizes. In small crystals, however, the trim pieces ordinarily are not salvageable insofar as discs over about $\frac{3}{8}$ inch diameter are concerned. The practice of purchasing large crystals would apply particularly to applications in which a large range of disc sizes is needed. Under present conditions of scant supply and high prices, it is largely a question of taking what is available. Since the small sizes greatly predominate, it is general practice to use the smallest raw crystal that will cut discs of the size immediately needed. A tolerance of 25% or so is added to the minimum dimension needed so that some leeway is had in avoiding cracks when the sawn slabs are diced.

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[9] Anderson, R. H., Cambridge Thermionic Corp., Cambridge, Mass. The value 11.08 is considered to be the best of those reported here, since the major experimental errors all tend to give low values.

[10] Cady, Piezoelectricity, New York (**1946,** p. 156).

The yield of slabs to be obtained from a raw crystal of known length can be calculated approximately from a knowledge of the thickness of the slabs and saw-blade used. The breakage during the sawing of tourmaline of average quality is only a few per cent. The yield of discs from irregular sawn slabs depends on a variety of geometrical and other factors: some representative data are given in Table 2, beyond. The loss of discs due to breakage during the dicing and machine lapping operations should run less than 10 per cent.

SHAPE. The efficiency of utilization of a crystal depends considerably on the shape. Very short crystals, as measured along the $Z = c$-axis, are undesirable since the broken ends, or much of the termination if the crystal is faced, must be discarded as waste and this may be a large proportion of the whole. In small sizes at least the crystals should be as long as they are wide. Crystals that are bounded externally or internally by fractures making small angles with Z are particularly wasteful, and productive of relatively small discs. Well rounded or barrel-shaped crystals are better suited geometrically to cutting discs than are sharply triangular or prismatically flattened crystals. These factors may seem of minor importance but can not be overlooked since a raw crystal weighing only a few pounds may cost a hundred dollars or more and the yield of thin discs therefrom may be only 25 per cent or so by weight at best.

FACES. It is very desirable that the raw crystals have one or more large and even prism faces present. These are needed to mount and orient the crystal preliminary to sawing. $\{0001\}$ faces can be used for the purpose as well, and also rhombohedral faces if the position of the Z axis can be established by inspection. Unfaced material is difficult to handle since the crystals ordinarily do not transmit enough light to be oriented by optical methods. Color bands parallel to the terminating rhombohedral faces are frequently present in tourmaline and can be used as a guide in orienting unfaced material.

Internal Quality

CRACKS. The amount of cracking present in the raw crystal is the most important factor determining its usability. A considerable and often surprisingly large amount of cracking can be tolerated provided that the cracks are discontinuous. The degree of cracking that is permissible is difficult to estimate, however, and shipments of raw material should be tested by trial sawing and dicing in order to determine usability. Through-going cracks, especially when associated with parallel growths in the crystal, usually cause failure. The nature of the fracture surfaces in tourmaline is a useful guide to quality. The best material has a glassy, conchoidal fracture, and non-usable material generally has a very uneven to coaly fracture. Examples of usable and non-usable tourmaline are shown in Figs. 5 and 6. Tourmaline used for oscillator-plate applications must be flawless—gem-grade tourmaline is best for the purpose—and that for ultrasonic generators should be nearly or entirely flawless.

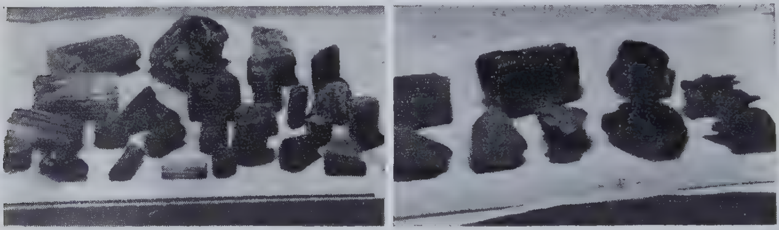

FIG. 5. *Right:* Badly cracked, non-usable black tourmaline from New England. *Left:* Selection of black Brazilian tourmaline of usable grade.

PARALLEL GROWTHS AND POROSITY. Some tourmaline crystals are aggregates of parallely grown, pencil-like, small crystals, such as shown in Fig. 6. The composite part may be only an overgrowth on an earlier-formed, relatively perfect crystal. Parallel growth is very undesirable in industrial tourmaline, since the crystals when sawn tend to break apart along the surfaces of juncture of the separate individuals. Other crystals have a related defect, consisting of threadlike openings and channels running parallel to Z. This sometimes grades into a parallel fibrosity.

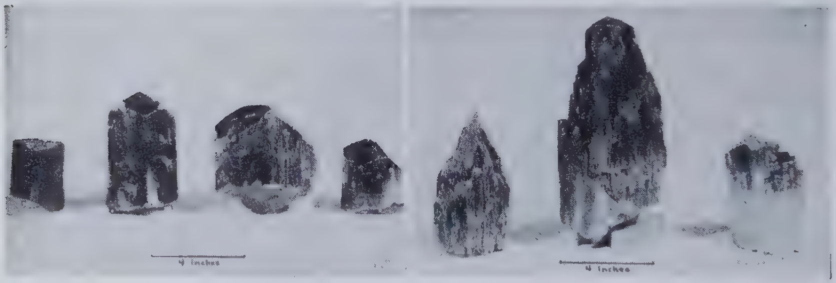

FIG. 6. *Left:* Usable, faced crystals of tourmaline from Madagascar. *Right:* Un-usable crystals of tourmaline, showing parallel-growth. The crystal on the right is from Mt. Mica, Maine, the others from Brazil.

Porosity of this nature is objectionable because discs containing throughgoing holes short out when metal-plated on the opposite sides.

COLOR. The color (or chemical composition) is not of consequence in itself in specifying tourmaline. Black, iron-rich types of tourmaline, however, usually are too badly cracked and friable to be useful. This is due to the early period of formation of such tourmaline in pegmatites, causing it to be solidly embedded in the matrix and then susceptible to fracture by mechanical stress. Black tourmaline from open cavities in some Brazilian occurrences proved to be of very high grade. Zoned Madagascar tourmaline often shows intense cracking confined to the colorless or pale pink zones, due presumably to differential thermal contraction.

TWINNING. Tourmaline, in distinction to quartz, is very rarely twinned and this feature is of no importance in specifying and grading the raw material. Only a few instances of twinning were observed in approximately 50 slabs of Madagascar and Brazilian tourmaline that had been etched in molten KOH. These comprised small isolated areas, amounting to only a few per cent of the total area of the slab, twinned apparently in all instances on $\{10\bar{1}1\}$.

Sources of Supply, and Price

The supply of raw material has in general been inadequate and at times critical. This has lent impetus to efforts to synthesize tourmaline.* The tourmaline imported into the United States in recent years has come from Madagascar and Brazil. About 2000 pounds were obtained from Madagascar via France during the war under exceptionally difficult circumstances. The cost of this material is not known. Recently small amounts have been obtained at $15 a pound. The Madagascar tourmaline in general is usable, but little so far seen is of above-average quality. It is notable for the occurrence of relatively large crystals, some individuals weighing 30 to 50 pounds apiece. The Brazilian tourmaline appears to originate entirely in Minas Geraes, particularly good material coming from the Governador Valladares district. It varies erratically in both quality and price, due to uncertainties as to specifications and how badly it is needed in the United States. The total amount of industrial grade tourmaline imported from Brazil since 1942 is not definitely known but probably is about 3000 pounds. During 1942 small amounts were sold at prices of $15 to $50 a pound. Later, in face of a recognized urgent need, prices are said to have been asked and paid of about $1000 a pound. The usual asking price has been in the neighborhood of $100 a pound, with no enthusiasm shown by buyers, but recently some material has become available at about $15 a pound. The latter price appears reasonable, and probably will be met or bettered by suppliers from non-Brazilian sources. Crystals over about 4 inches in size generally sell at a premium. Very large crystals, over about 7 inches in diameter, are not needed for gauge applications and are too large to be handled by conventional sawing equipment.

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* Frondel, C., Hurlbut, C. S., Jr., Collette, R. C., *Am. Mineral.*, **32**, 680–681 (1947).

Tourmaline occurs widely in the United States but intensive search so far has not developed any large supply of usable material. Black tourmaline from pegmatites in Colorado, California, the Black Hills and numerous localities in New England when sawn and tested almost invariably proved too badly cracked and friable for use. A few usable crystals were obtained from pegmatites at Mt. Mica and Topsham, Maine. The pink tourmaline from Pala, California, is usable but the available crystals are too small in size. About 500 pounds of black tourmaline was obtained from a pegmatite near Overlook, New York, during the war and sold in the United Kingdom at prices of $1 to $5 a pound. Some of the individual crystals were as much as 10 inches in diameter. This material is believed to have been used as extremely thick slabs and is too badly cracked for use in ordinary gauges.

Manufacture of Tourmaline Discs

The methods and equipment used in sawing raw tourmaline crystals preparatory to cutting discs are essentially those used with quartz. The raw crystal is cemented down by a prism face to a supporting plate. It is then mounted on the bed of a diamond saw and slabs are cut at right angles to the $Z=c$-axis as shown in Fig. 7. The piezoelectric response of Z sections is not very sensitive to small angular deviations from perpendicularity and an angular tolerance of 2° or so, easily attained by mechanical alignment procedures, is permissible. Experience has shown that there is a minimum thickness of the sawn slab in relation to its width (and similarly in the final thickness of the discs cut and lapped therefrom, as noted beyond) at which breakage during sawing and subsequent operations is reduced to a practical minimum. The data given below refer to tourmaline of average quality, and the thicknesses in the larger sizes can be reduced somewhat in material of high quality.

Cross-dimension of the raw crystal (width of slab)	Minimum thickness of sawn slab
1 inch	0.035–0.040 inch
$1\frac{1}{2}$	0.040–0.045
2	0.050–0.060
3	0.070–0.090
6	0.100–0.140

It is assumed that a superior type of sawing machine is employed,[11] with a true-running diamond-edged blade. In view of the high cost of the raw material it is essential to use as thin a saw blade as practical. The minimum blade thicknesses are comparable to the slab thicknesses, or

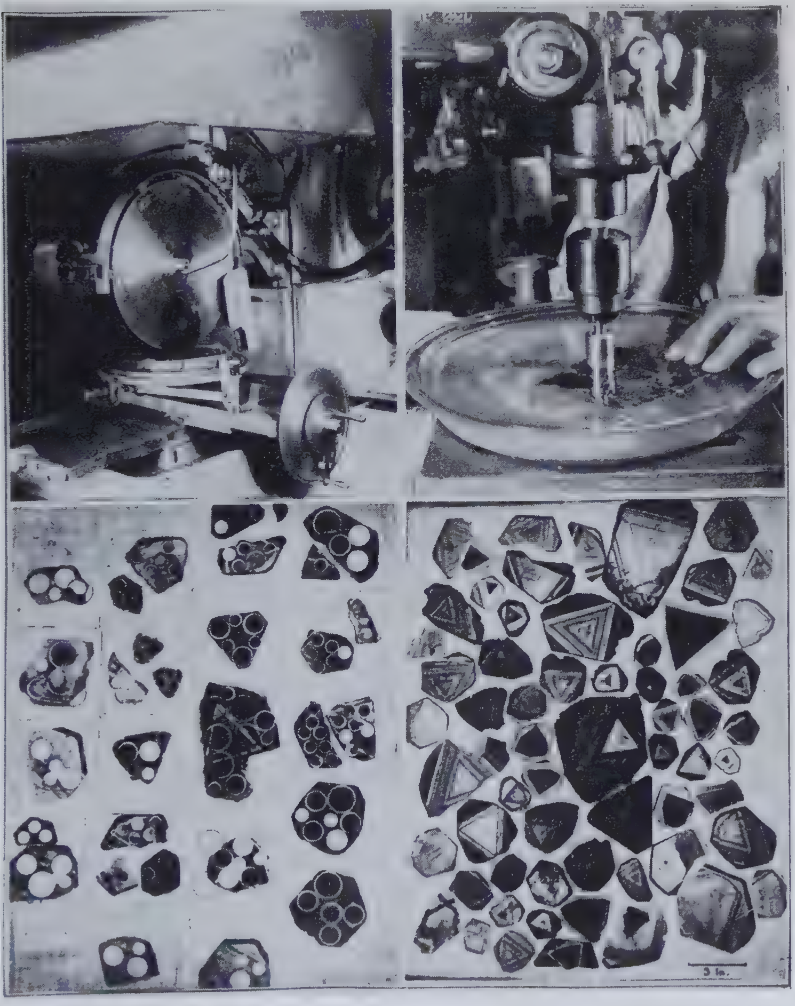

FIG. 7. *Upper, left:* Large tourmaline crystal being sawn with a diamond-edged blade. *Upper, right:* cutting discs with a diamond-edged rotary tool. *Lower, left:* Diced-out slabs of tourmaline. *Lower, right:* Color banding in *Z*-cut (basal) slabs of Madagascar tourmaline.

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[11] Cf. Parrish, *Am. Mineral.*, **30**, 371, 389 (1945).

somewhat less in the larger sizes, so that roughly half of the raw material is lost as saw dust in the first operation. Tourmaline saws and laps more readily than quartz, although of the same hardness. An idea of the number and size distribution of discs to be obtained from tourmaline of average quality can be had from Table 2, taken from actual production records. The disproportionally small yield of 1½ inch discs from large crystals shown by this table reflects the fact that slabs not sufficiently free from cracks to afford 1¾ inch discs, the first size cut, generally do not yield any immediately smaller sizes but only discs of very much smaller size, usually ½ inch or less. The proportion of 1½ inch relative to 1¾ inch discs increases with decreasing size of the raw crystal since the size of the slab then becomes a relatively important yield-determining factor.

TABLE 2. YIELD OF DISCS FROM AVERAGE QUALITY MADAGASCAR TOURMALINE

Approximate diameter of raw crystal	Number of crystals	Total weight	Number of slabs obtained, .065″ thick	Number of discs obtained (cut in order of decreasing size)						
				1¾″	1½″	1¼″	1″	¾″	½″	¼″
3¼″–3¾″	9	23 lb. 3 oz.	247	181	35	74	201	167	383	
2″ –3¼″	13	14 11	272	92	63	69	93	106	353	
1″ –2″	32	11 8	355*	22	36	67	48	70	444**	
Totals	54	49 lb. 6 oz.	874	295	134	210	342	343	1180	>2000 (est.)

* Includes 91 slabs cut 0.130″ thick.
** Includes 160 discs cut 0.130″ thick.

The next step in manufacture is in dicing out discs or rectangular plates from the sawn slabs. The slabs are first cemented down with a beeswax-rosin mixture to a thick glass plate. Discs are cut out to dimension with a tubular, diamond-edged tool mounted on a high speed drill press (see Fig. 7). The tool should be cooled during use, such as by immersing the mounted slab in kerosene or water-soluble oil. The slabs should be carefully inspected before dicing, so that discs of various sizes can be accommodated to the cracks or other defects that may be present. Rectangular plates can be cut by means of dicing saws, described elsewhere.[11]

Usually the discs as cut are at the thickness desired for use in gauges, but sometimes it may be necessary to further reduce the thickness. This can be done by conventional quartz-working techniques on drill-press laps.[11] An assortment of lapped discs is shown in Fig. 8. In general it is desirable to use the thinnest discs practical in order to give a minimum thicknesss to width ratio in the finished gauge. The minimum thickness ordinarily is set by the quality of the raw material available and in part by the method of edge-insulation employed in the gauge. Experience has shown that the values given below are practical with tourmaline of average quality. With flawless tourmaline it is possible to work down to thicknesses of a few thousandths of an inch, or even less, in discs up to $\frac{1}{2}$ inch or so in diameter.

Disc diameter	Minimum disc thickness
$\frac{1}{2}$ inch	0.020–0.025 inch
1	0.025–0.035
$1\frac{1}{2}$	0.040–0.050
2	0.055–0.070
3	0.080–0.120

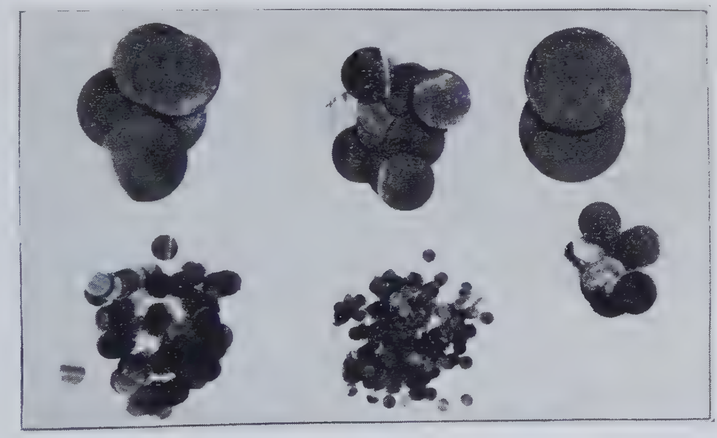

FIG. 8. Selection of lapped tourmaline discs, ranging in thickness from 0.015 inch in the smallest size ($\frac{1}{4}$ inch diameter) to about 0.070 inch in the largest ($1\frac{7}{8}$ inch diameter).

POTASH-RICH ROCKS OF THE ESTEREL, FRANCE*

RUTH D. TERZAGHI

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ABSTRACT

An apparently fresh, vitreous obsidian of the Esterel region has a normal chemical composition, whereas analyzed specimens of devitrified obsidian and of rhyolite are abnormally rich in potash and/or silica. The contrast between the composition of the fresh obsidian and that of the other rhyolitic rocks of the region, as well as microscopic features of the rhyolite and devitrified obsidian, suggest that these rocks owe their abnormal composition to hydrothermal enrichment in potash and/or silica.

INTRODUCTION

The term *potash-rich rock* is applied to any igneous rock whose normative feldspar content corresponds to a point in the orthoclase field of the feldspar equilibrium diagram (Bowen, 1928, Doggett, 1929). The problematical nature of the origin of these rocks was first discussed by Bowen (1928) who suggested a manner in which they might result from crystallization-differentiation. Other hypotheses of their origin were presented by the writer (Terzaghi, 1935).

Final conclusions regarding the origin of these rocks can be drawn only on the basis of field and laboratory investigations of individual occurrences. Studies of this kind which have already been made indicate that potash-rich rocks may originate in more than one way. The earliest of these studies dealt with some volcanic rocks of the Yellowstone Park region (Fenner 1936) and demonstrated the secondary origin of a considerable part of the potash contained in some of these rocks. Another mode of origin of potash-rich rocks has been indicated by Esper S. Larsen and Esper S. Larsen, 3rd (1938), who showed that potash-rich rhyolites of the San Juan region can be explained as a result of fractional crystallization involving the separation of a single alkalic feldspar richer in soda then the liquid phase. The present article deals with a group of potash-rich rocks which, like those of the Yellowstone region, owe their abnormal chemical composition to hydrothermal alteration.

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* Contribution from the Department of Mineralogy and Petrography, Harvard University, No. 292.

The rhyolites and obsidian which are the subject of this article have been mapped and described by Albert Michel-Lévy (1911) to whose publication the reader is referred for a detailed account of them. The general description of the field relations, given in the next section, is based on this work. Megascopic secondary features, such as veins and druses, and other details of occurrence, were observed by the writer during three weeks spent in the field. The description of microscopic features is based on the writer's examination of over one hundred thin sections of Esterel rocks in the Mineralogical Laboratory of the Sorbonne. These were very kindly placed at the disposition of the writer by Professor Michel-Lévy, whose courtesy and helpfulness she acknowledges with gratitude. Thanks are also due to Mr. LeRiche of the same laboratory for taking the photomicrographs which illustrate this article.

General Description

The Esterel is a region of low mountains and hills, roughly 16 km. by 25 km. adjacent to the Mediterranean coast, between Cannes and St. Raphael. It is mapped topographically on the eastern part of the Fréjus sheet and the western part of the Cannes sheet, both of which were published by the Geographical Service of the French Army in 1933. The scale of both maps is 1/50,000.

Schist outcrops in the northern part of the region. It is overlain by sandstones and bituminous shales of Carboniferous age. Fluorite occurring in these was being mined at the time of the writer's visit in 1939. An angular unconformity separates the Carboniferous rocks from those of Permian age, which are gently folded. The latter include terrestrial sandstone, shale, and conglomerate, a few small intrusive bodies of dark-colored igneous rock, and the rhyolites and obsidian which are the subject of this article. The oldest of the rhyolitic rocks is the platy rhyolite porphyry or *porphyre tabulaire* of Michel-Lévy; closely associated with it is the slightly younger red rhyolite porphyry (*porphyre amarante*); the youngest of the three extrusive rocks of the area is a spherulitic rhyolite (*pyroméride*) which has vitreous and devitrified facies.

Veins and Druses in Rhyolites

The presence of veins and druses throughout the rhyolitic rocks of the Esterel indicates that the extrusion of these rocks was followed by a period in which hot aqueous solutions, and possibly gases, were abundant.

Veins of the commonest type are twenty centimeters or less in thickness and consist of dense, fine-grained reddish brown material. Microscopic examination shows that this material is a mixture consisting of an amorphous substance, probably opal, calcite, minute red particles which appear to be hematite, and one or more minerals having a low birefringence, which are too fine-grained for microscopic determination. Some of the largest of these veins are associated with lens-shaped masses of a clay mineral, one to two centimeters in thickness.

Quartz veins and druses occur locally in all of the rhyolites. Magnetite is found in the central part of some of the druses in the red porphyry and a kaolinite-like substance occupies the central part of quartz druses in some of the rhyolite dikes.

Relatively volatile minerals are not uncommon in the rhyolites. In the Maure-Vieille valley, the writer found fluorite in vugs in a rhyolite dike which represents a vent of the youngest flow, as well as in vesicular rhyolite porphyry of the oldest flow. Galena was found in cavities in a devitrified glass.

Spherulitic Rhyolite and Obsidian

Introduction

The spherulitic rhyolite and obsidian represent the youngest flow of the region. The composition of these is better known than that of the older porphyry, owing to the larger number of analyses which have been made, and they will therefore be discussed first.

Chemical Composition

Nine analyses of the spherulitic rhyolite and obsidian, as well as two of the porphyry, were made by Pisani and published by Michel-Lèvy in 1911. These are given in Table 1 and the norms in Table 2. Figure 1 shows the normative feldspar content of the rocks, and Fig. 2 the normative orthoclase, plagioclase, quartz, and corundum.

Clearly unaltered rock outcrops at only one[1] of the six localities from which specimens were taken for analysis. The composition of this rock, a vitreous obsidian, therefore provides the one reliable indication of the original composition of the lava of the youngest flow, to which it belongs. The composition of this rock (Analysis No. 11) is normal. The molecular ratio of potash to soda is only 0.5, and the rock is therefore not potash-rich. The molecular proportion of alumina is exactly equal to the sum

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[1] Colle de la Motte; this locality, not indicated on the 1933 topographic map, is reached by a path which branches eastward from the Reyran valley road at a point 5.3 km. from Fréjus, and follows the south side of the *colle* (hill).

TABLE 1. ANALYSES OF RHYOLITES AND OBSIDIANS
(Michel-Lévy, 1911)
Analyst, Pisani

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
TiO_2		0.20	0.13		0.08		0.06	0.13	0.06	0.05	0.06
SiO_2	88.40	82.61	81.80	81.20	78.11	77.10	76.40	76.25	75.90	74.60	72.20
Al_2O_3	4.85	8.30	7.65	9.40	11.50	10.64	10.60	11.10	11.43	11.23	10.75
Fe_2O_3	1.61	2.54	1.88	1.35	1.60	1.55	1.40	1.68	1.70	1.52	0.89
FeO		0.45	0.70					0.45	0.30		0.80
CaO		0.26			0.51			0.39		0.45	0.45
MgO	0.39		0.64	0.77	0.25	1.05	0.38	0.26	0.26	0.25	0.65
K_2O	2.45	2.98	2.75	4.55	6.26	5.98	7.45	7.85	6.40	8.71	3.17
Na_2O	0.54	1.44	2.97	2.45	0.54	0.64	2.57	1.16	2.47	1.61	3.95
Loss on ignition	1.30	0.75	1.01	0.70	1.90	2.50	1.60	1.00	0.89	1.70	7.32
Total	99.54	99.53	99.53	100.42	100.75	99.46	100.46	100.27	99.41	100.12	100.24

(1) Spherulitic rhyolite, flow, Grand Defends-Boulouris.
(2) Platy porphyry, flow, Chemin Auriasque.
(3) Spherulitic rhyolite, dike, Logement des Cantonniers.
(4) Spherulitic rhyolite with residue of obsidian, flow, Colle de la Motte.
(5) Spherulitic rhyolite, flow, Col des Sacs.
(6) Devitrified obsidian, flow, west side, Collet Redon.
(7) Devitrified obsidian with transition to spherulitic rhyolite, flow, Colle de la Motte.
(8) Porphyry, Mont Vinaigre.
(9) Spherulitic rhyolite, dike, Mont Vinaigre, 500 meters south of Duchesse.
(10) Devitrified obsidian, north of summit of Mont Pelet.
(11) Black obsidian, flow, Colle de la Motte.

TABLE 2. NORMS OF OBSIDIANS AND RHYOLITES
(Numbers refer to analyses given in Table 1)

	1	2	3	4	5	6	7	8	9	10	11
Q	75.30	62.22	53.10	46.32	48.18	47.70	35.82	37.98	36.60	31.98	34.74
or	14.51	17.79	16.68	27.24	37.25	35.58	44.48	46.70	37.81	51.71	18.90
ab	4.56	12.05	23.58	20.96	4.72	5.24	12.58	9.96	20.96	8.91	33.54
an		1.39			2.50			1.67			2.22
C	1.30	2.14		0.46	3.06	2.89			0.41		
ac			1.39				3.70			4.16	
ns							1.22				
di								0.22		1.30	
wo										0.23	
hy	1.00		1.60	4.01	3.11	5.24	1.00	0.60	0.70		2.13
mt		0.70	1.86					0.93	0.70		1.39
il		0.46	0.30		0.15		0.15	0.30	0.15		0.15
hm	1.68	2.08	0.64					1.06	1.28		

of the alkalis plus lime, and the silica content is 72 per cent, or, after deducting loss on ignition, 78 per cent.

The composition of the other analyzed specimens varies through an extremely wide range, and nearly all of them are strikingly different in composition from the vitreous obsidian. An abnormally high potash content and a high potash-soda ratio characterize most members of the group, including a devitrified glass (No. 7) and a rhyolite (No. 4) collected within a few hundred feet of the outcrop of fresh obsidian. Some of the analyzed specimens are distinguished by a very high silica content, and by an excess of alumina over the sum of the alkalis plus lime, which corresponds to corundum in the norm and to secondary sericite, chlorite, and clay minerals in the mode. It appears highly improbable that the original composition of rock representing a single flow could be characterized by variations of such magnitude and kind. Furthermore, the presence of normative corundum is in itself an indication that the rocks are altered. On the basis of chemical composition alone it would therefore be difficult to escape the conclusion that the majority of the analyzed specimens represent altered rock.

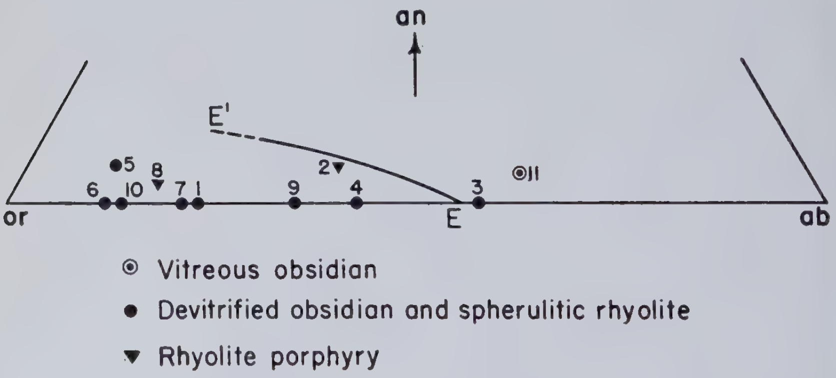

FIG. 1. Normative feldspar content of rhyolitic rocks of the Esterel.
Line *E–E′* represents the probable position of the orthoclase-plagioclase field boundary. Numbers refer to analyses given in Table 1.

Inspection of Fig. 2 suggests that the differences between the composition of the vitreous obsidian (No. 11) and that of the other rhyolitic rocks can be explained as the result of one or more of several different alteration processes, including replacement of lime and/or soda by potash (Analyses 7, 9, and 10), replacement of feldspar by quartz (Analyses 1, 3, 4, 5, and 6) and the alteration of feldspar to sericite or a clay mineral (Analyses 1, 5, and 6). Microscopic features which suggest that these processes have in fact taken place will be described in the following paragraphs.

Evidence of Alteration of Devitrified Obsidian

The writer has noted elsewhere (Terzaghi 1935) that there are no potash-rich vitreous obsidians among the rocks of which analyses are given in Washington's tables (1917) whereas there are several potash-rich devitrified obsidians from various parts of the world. This fact suggests that both the high potash content and the crystalline character with which it is associated may be due to the same cause, presumably

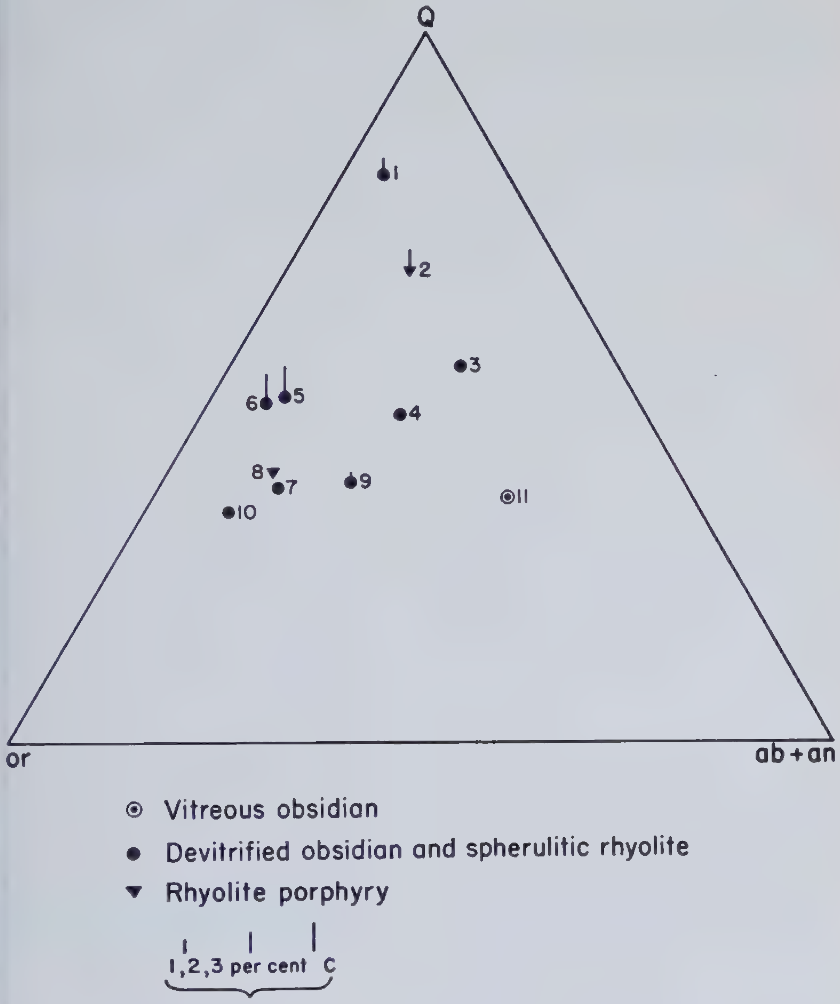

Fig. 2. Normative quartz, orthoclase, plagioclase, and corundum content of rhyolitic rocks of the Esterel.

Quartz, orthoclase, and plagioclase content, recomputed to 100 per cent, are shown in the triangular diagram; the percentage of corundum in the norm is indicated by the length of the vertical line attached to the symbol representing each of the specimens which contain normative corundum.

hydrothermal alteration. This statement does not, of course, imply that devitrification cannot take place without the aid of percolating solutions; it does, however, point to the necessity of a careful examination of devitrified obsidians for evidence of alteration. Such evidence is found in devitrified obsidian of the Esterel and will be described below.

Field evidence of a causal relationship between alteration by percolating solutions and devitrification is found in the limitation of devitrification to the immediate vicinity of cracks in an obsidian outcropping in the gully located by the co-ordinates 958W and 141.4N on the Fréjus sheet.

Evidence of another kind is found in the thin section of which a part is shown in Plate 1, Fig. 1. In the rock which this section represents, crystallization evidently took place in three distinct stages. In the first stage, crystallites formed and accumulated, apparently in random orientation, in spheroidal agglomerations whose shape suggests that the lava was still in motion during this stage. A part of such an agglomeration is visible in the photomicrograph. The second stage of crystallization is represented by feebly polarizing, plume-like structures present in the crackled material occupying a wedge-shaped area in the central part of the photomicrograph. (These structures are not visible in the photomicrograph, which was taken in ordinary light.) The appearance of these suggests that active flow had ceased when they developed. Their formation evidently preceded the chilling which led to the development of perlitic cracks in the completely amorphous lava. The third and last stage of crystallization is represented by relatively well-developed individuals of alkalic feldspar occurring in the material which exhibits perlitic cracks. These crystals are not visible in the photomicrograph (Pl. 1, Fig. 1), but similar ones, commonly with a rhombic cross section, are plainly seen in Plate 1, Fig. 2. Their formation appears to have followed that of the perlitic cracks, and we may therefore conclude that they developed when the lava had already hardened. In spite of the rigidity of the glass in which they formed, these crystals are much larger and better developed than those formed in earlier stages when the lava was fluid. In order to account for their relative perfection, it is necessary to suppose that their development was aided by aqueous solutions percolating through the cracks in the obsidian and it appears most probable that they originated by the replacement of vitreous material. The solution which deposited them did not attack the crystalline material already present, probably because it was less soluble and contained fewer or smaller cracks than the adjacent vitreous material.

Plate 1, Fig. 2, shows part of a thin section of devitrified obsidian from another locality (Colle de la Motte). Like the specimen of devitrified glass shown in Fig. 1 (Pl. 1), this contains relatively well developed crys-

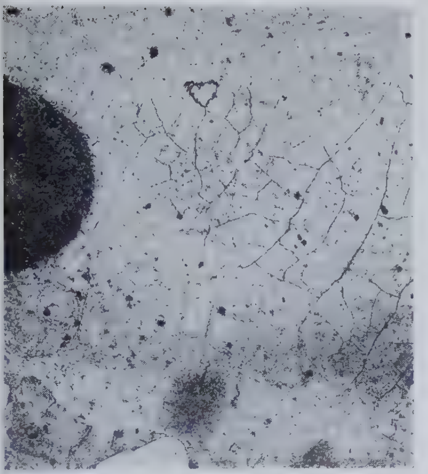

FIG. 1.—Devitrified Obsidian.

Perlitic cracks characterize originally glassy portions, whereas irregular cracks occur where incipient crystallization preceded final chilling. Ordinary light. ×20.

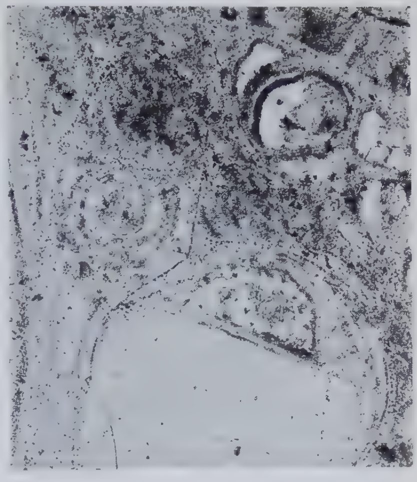

FIG. 2.—Devitrified Obsidian.

Rhombs of pink alkalic feldspar occupy masses surrounded by perlitic cracks. A veinlet of alkalic feldspar may be seen at the left-hand side. Ordinary light. ×41.

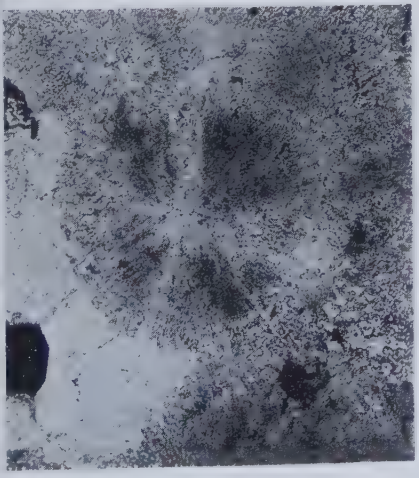

FIG. 3.—Spherulitic Rhyolite.

Spherulites are locally replaced by quartz. The clear mineral is quartz, large stippled areas represent a clay mineral, and black areas, magnetite in part altered to hematite. Ordinary light. ×76.

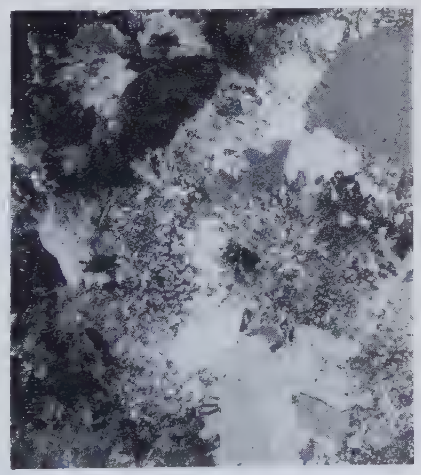

FIG. 4. Spherulitic Rhyolite.

Feldspar in the spherulites is in part sericitized and in part replaced by quartz in the vicinity of a pocket or veinlet containing quartz and sericite. Crossed Nicols. ×19.

PLATE 1. Photomicrographs of Devitrified Obsidian and Rhyolite.

tals of alkalic feldspar, interpreted as an effect of hydrothermal alteration. A veinlet consisting chiefly of alkalic feldspar, visible adjacent and parallel to the left-hand side of the photomicrograph, is likewise attributed to percolating hydrothermal solutions. In connection with the microscopic evidence that this obsidian has been enriched in alkalic feldspar, it is of interest to note that an analyzed specimen of devitrified obsidian from the same locality contains 7.45 per cent K_2O, in contrast to 3.17 per cent K_2O contained in the fresh vitreous obsidian from an adjacent outcrop.

Evidence of Alteration of Spherulitic Rhyolite

In most localities, the spherulitic rhyolite appears to be altered. The feldspar phenocrysts are generally dull, the rock commonly has a bleached appearance, and in places it is in part altered to a white powder. Even in new road cuts and in quarries, it is generally so decomposed along cracks and joints that it is impossible to obtain a good hand specimen.

Details found in some of the thin sections suggest the nature of the alteration processes. Plate 1, Fig. 3, shows a spherulitic rhyolite in which the spaces between spherulites are occupied by coarse-grained quartz, small quantities of a fine grained clay mineral, and magnetite locally altered to hematite, all apparently of hydrothermal origin. The spherulites are in part replaced by quartz. As a result of alteration, this rock was enriched in quartz and ferric oxide. Analysis No. 4 represents a spherulitic rhyolite from the same locality. A comparison of the norm of this rock with that of the vitreous obsidian suggests that it has been enriched in silica and that soda and lime have been in part replaced by potash.

Similar phenomena are illustrated by Plate 1, Fig. 4, which shows part of a thin section of a spherulitic rhyolite. The feldspar contained in the spherulites has been locally replaced by quartz and in part sericitized in the zone contiguous to the elongated interstitial masses consisting of sericite and coarse grained secondary quartz. The net effect of the alteration of this rock was the removal of soda, the addition of silica and possibly of potash, and an increase in the molecular ratio of alumina to alkali-plus-lime.

The rock shown in Plate 2, Fig. 1, has also been enriched in quartz and sericite, but the resulting texture is different from that shown in Plate 1, Fig. 4. Each of the rounded areas in the groundmass represents a spherulite almost completely replaced by a single quartz individual. Locally the groundmass contains sericite. As shown in the photomicrograph, sericite also occurs in a veinlet intersecting a quartz phenocryst,

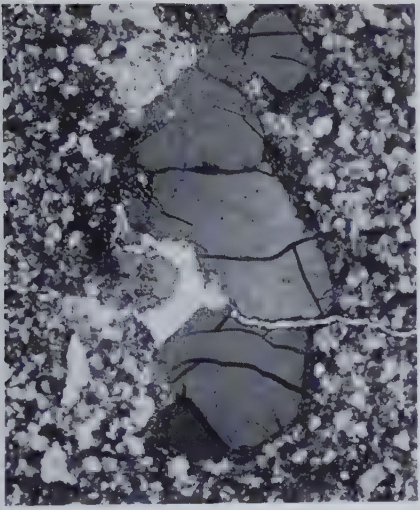

FIG. 1.—Spherulitic Rhyolite.

Showing veinlet of sericite cutting quartz phenocryst. Crossed Nicols. ×33.

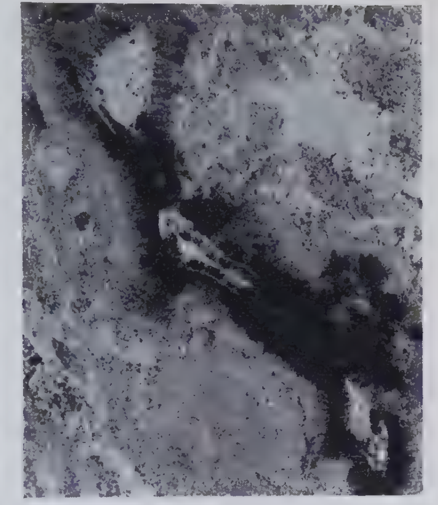

FIG. 2.—Spherulitic Rhyolite.

Showing veinlet of hematite-stained alkalic feldspar with quartz in center. Ordinary light. ×19.

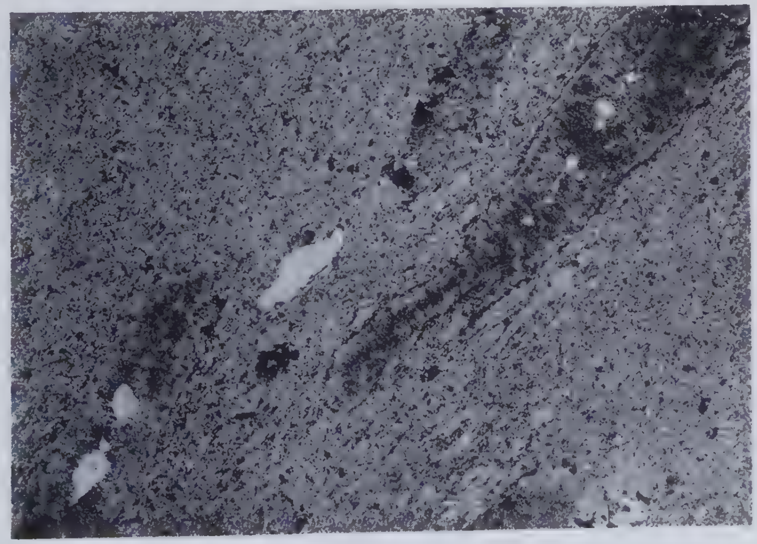

FIG. 3.—Platy Porphyry.

Showing vesicles filled with secondary alkalic feldspar and quartz. Ordinary light. ×48.

PLATE 2. Photomicrographs of Rhyolite.

and in a cavity within the same phenocryst. Other phenocrysts not shown in the photomicrograph have been completely replaced by sericite and quartz, possibly accompanied by other secondary minerals.

Plate 2, Fig. 2, shows part of a thin section of a rock which has undergone at least two stages of alteration. The first involved partial replacement of the groundmass by minute quartz veinlets and alteration of feldspar to clay mineral. This process was followed by the deposition of alkalic feldspar in irregular veinlets, one of which is shown in the photomicrograph. Analysis No. 6 represents a devitrified obsidian from the same locality. This rock is richer in silica and potash than the unaltered rock (No. 11) and contains normative corundum. It has therefore probably undergone the same alteration processes as the rock shown in Plate 2, Fig. 2.

Microscopic veinlets of quartz and opal are common in the spherulitic rhyolite. They appear to represent a later stage of alteration than do the replacement processes described in the preceding paragraphs.

Rhyolite Porphyry

There are few outcrops of perfectly fresh rhyolite porphyry. In most localities, the phenocrysts are dull and in some places they have been completely altered to a clay mineral. Locally the rock is pale green and is readily crumbled.

An inspection of the thin sections shows that the phenocrysts of alkalic feldspar are commonly partly altered to a granular material characterized by low index of refraction and low birefringence, or, more rarely, to sericite. Plagioclase was not found in any of the thin sections examined but in places the red porphyry contains masses of a white kaolinite-like material having a rectangular or a rounded cross section, from 1 to 3 mm. in greatest dimension. These may represent completely altered plagioclase phenocrysts.

The porphyry generally contains elongated vesicles lined by fibers most of which consist of alkalic feldspar. The centers of many of the vesicles are filled with quartz and, in at least one locality, calcite. In the platy porphyry, the vesicles range in width from a few hundredths of a millimeter to several millimeters, and in length from about one tenth millimeter to ten millimeters. They constitute as much as 30 per cent of some specimens. Plate 2, Fig. 3, representing a part of a thin section of platy porphyry, shows some of these vesicles. In the red porphyry, the feldspar-lined vesicles are not longer than 0.1 mm. and in most specimens of this rock those which are readily visible constitute less than five per cent of the rock.

In some specimens of porphyry, quartz occupying the central part of the vesicles appears locally to have replaced feldspar. In a few such specimens, the secondary feldspar is altered to an opaque brown substance, probably consisting of iron-stained clay mineral.

The microscopic features described in the preceding paragraphs suggest that the porphyry has been subjected to the same alteration processes as the spherulitic rhyolite, i.e., potash enrichment in some localities and in others, enrichment in silica and impoverishment in both alkalis owing to alteration of feldspar to a clay mineral. The chemical analyses support this conclusion. One of these (No. 8) represents a specimen of red porphyry in which the secondary feldspar is relatively fresh. This rock is characterized by an abnormally high potash content (7.85 per cent). The other analysis (No. 2) represents a specimen of platy porphyry in which much of the feldspar has been altered to clay mineral. As would be expected, the total alkalis in this rock are low, and the molecular ratio of alumina to the sum of the alkalis plus lime is greater than one. Potash is considerably in excess of soda, possibly owing to selective leaching of soda.

Conclusions

The abundance of veins and druses, some of which contain relatively volatile constituents, indicates that hot solutions and possibly gaseous emanations were active in the region after the eruptions of rhyolitic lava took place. Few of the rocks of rhyolitic composition remained completely unchanged by these solutions, but the nature of the reactions between solutions and rocks is most clearly indicated by microscopic features of the spherulitic rhyolite. These show that under some conditions alkalic feldspar was completely dissolved and replaced by quartz; under others, at least a part of the alkali content of the feldspar was removed and the residue crystallized *in situ* as sericite or as a clay mineral. Under still other conditions, alkalic feldspar, or sericite, or a clay mineral was deposited as a vein mineral. The deposition of notable quantities of quartz accompanied the deposition of clay mineral and of sericite, whereas in general only a small quantity of quartz was deposited contemporaneously with secondary feldspar. Some of the rhyolitic rocks have undergone first leaching of feldspar followed by deposition of feldspar or sericite or a clay mineral; some have been subjected to only one of these processes.

The presence in potash-rich altered rocks of secondary alkalic feldspar and of vein sericite of extraneous origin strongly suggests that a considerable part of the large quantity of potash contained in many of the altered rocks was acquired during alteration. The source of the secondary potash was possibly two-fold. Some of it may have been introduced by hydrothermal solutions or gaseous emanations originating from an underlying body of magma. Another part of the potash was probably derived by local leaching of the rhyolite itself. The quantitative importance of this source is indicated by the fact that about one fourth of the thin sections examined bear clear evidence of more or less advanced replacement of spherulites by quartz, like that illustrated by Plate 1, Fig. 3. The potash thus leached from the rhyolite in one place was carried on in solution and was available for potach enrichment elsewhere.

These conclusions regarding the dual origin of the secondary potash in the Esterel region are in general agreement with those presented by Allen (1934, 1935), Allen and Day (1934) and by Fenner (1936) in their studies of the thermal waters and the altered rhyolite of the Yellowstone Park region. In this area, the rhyolite is still in the process of alteration by thermal water containing alkali halides and bicarbonates. The halides are believed to originate as gaseous emanations from an underlying body of magma, whereas the presence of bicarbonates is attributed to a reaction between dissolved carbon dioxide of magmatic origin and alkalis leached from rhyolite.

Irrespective of whether the alkalis contained in the thermal waters of the Esterel were of magmatic origin or derived by the leaching of already solidified rock, it is not probable that the quantity of potassium in solution was in excess of that of sodium. Hence the question arises as to whether these waters were capable of effecting a substitution of potassium for sodium in the rock through which they passed. An affirmative answer to this question has been provided by Fenner (1936) who found that substitution of potassium for sodium in the rocks of the Yellowstone region "goes on until the waters are so depleted of potassium and enriched in sodium that the ratio of the two becomes 1:34."

References

Allen, E. T. (1934), Neglected factors in the development of thermal springs: *Proc. National Academy of Sciences*, **20**, 345–349.

——— (1935), Geyser basins and igneous emanations: *Econ. Geol.*, **30**, 1–13.

——— and Day, Arthur L. (1934), Hot springs in the Yellowstone National Park: *Proc. Fifth Pacific Science Congress*, Victoria and Vancouver, B. C., Canada, **3**, 2275–2283.

Bowen, N. L. (1928), The Evolution of the Igneous Rocks, Princeton.

Doggett, R. A. (1929), The orthoclase-plagioclase equilibrium diagram: *Jour. Geol.*, **37**, 712–716.

Fenner, Clarence (1936), Yellowstone Park borehole investigations: *Jour. Geol.*, **44**, 226–315.

Larsen, Esper S., and Larsen, Esper S. 3rd (1938), Petrologic results of a study of the minerals from the tertiary volcanic rocks of the San Juan Region, Colorado: Pt. 8, Orthoclase, *Am. Mineral.*, **23**, 417–429.

Michel-Lévy, Albert (1911), L'Esterel.—Etude stratigraphique, pétrographique, et tectonique: *Service de la Carte Géologique de France, Bull.* **130.**

Terzaghi, R. D. (1935), The origin of the potash-rich rocks: *Am. Jour. Sci.*, **29**, 369–380; **30**, 141–142.

Washington, H. S. (1917), Chemical Analyses of Igneous Rocks: *U. S. Geol. Survey, Prof. Paper* **99.**

SIMPLE FIELD TEST FOR DISTINGUISHING MINERALS BY ABRASION pH*

Rollin E. Stevens and Maxwell K. Carron

Abstract

A simple field test is described for distinguishing minerals by estimating the pH of suspensions made by grinding them in water. The term abrasion pH is proposed to designate the pH values obtained by this grinding technique, which may differ from pH values obtained by shaking previously ground minerals in water. Soft minerals are scratched in one or two drops of water on a streak plate for about a minute to form a milky suspension and the resulting pH of the solution estimated with indicator papers. Hard minerals and those that absorb water are ground with a few drops of water in an agate mortar for about a minute. Abrasion pH values are given for about 280 mineral species, many of them confirmed repeatedly by determinations on specimens from different localities. Abrasion pH values of minerals range from 1 to 12. Many minerals whose compositions vary because of isomorphous replacements yield a range of values that reflect the varying content of alkali- or acid-forming materials, whereas minerals of fixed compositions show little variation in abrasion pH for each mineral species. Many minerals similar in appearance but differing in composition are easily distinguishable by the abrasion pH test, for example calcite from dolomite or magnesite, talc from pyrophyllite, and muscovite from phlogopite.

Introduction

Although frequently simple tests in the field may be sufficient to identify a mineral definitely, some specimens may require study of their optical properties and chemical composition in the laboratory before their identity or value can be established. Any additional property by which minerals can be definitely identified in the field, therefore, seems worthy of the attention of geologists and mineralogists.

The abrasion pH of a mineral is a property that can be estimated easily and quickly for field identification of a specimen. Although the precise determination of the pH of solutions requires considerable equipment, an estimate can be obtained by simple means. In the technique described below for the determination of abrasion pH the only equipment needed is a porcelain streak plate, small agate mortar and pestle, pH indicator papers, and distilled water or water of low salinity.

The alkaline reaction of some minerals has been noted in previous investigations. Kenngott[1] found that many silicates give alkaline reactions to moistened test paper. Clarke[2] treated a number of powdered silicate minerals with water containing phenolphthalein, noting the intensity of color produced, and thus determined roughly the extent to which they were decomposed. Analyses by Steiger[3] showed a discrepancy between the intensity of the color and the quantity of alkali found in solution.

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* Published by permission of the Director, U. S. Geological Survey, Washington, D. C.

[1] Kenngott, A., Über einige Erscheinungen beobachtet an Natrolith: *Neues Jahrb.*, 77 (1867).

Atkins[4] discussed the application of pH to the study of geological problems and made several measurements on minerals. Stevens[5] made colorimetric and electrometric pH measurements on silicate minerals crushed in water. Umegaki[6] studied the pH values of water suspensions of plagioclase feldspars and carbonate minerals, which were first ground in air to pass a 200 mesh sieve and shaken with water for varying time intervals.

COMPARISON OF RESULTS BY DIFFERENT METHODS OF ATTACK.

DEFINITION OF ABRASION PH.

The pH values presented in this paper and those previously reported by Stevens[5] on silicates of alkaline reaction are generally higher than the carefully determined values of Umegaki.[6] Probably this discrepancy is due to the different methods of attack of the minerals. Umegaki's results were obtained by placing the previously ground mineral in water and shaking for as long as 2½ hours, whereas the results here reported were determined by grinding the mineral in water. In grinding the mineral in water increased hydrolysis results from the continuous exposure of new surfaces to attack and perhaps from localized rise in temperature and pressure during the abrasion of the mineral grains.

Because of these discrepancies, apparently resulting from different methods of attacking the mineral, the term abrasion pH is adopted in the present study to designate the pH resulting from grinding the mineral under water.

HYDROLYSIS OF MINERALS

In an elementary treatment, salts may be considered the product of the reaction between an acid and an alkali. Thus, representing a hypothetical acid by HA and a hypothetical alkali by BOH their reaction may be represented as follows:

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[2] Clarke, F. W., The alkaline reaction of some natural silicates: *U. S. Geol. Survey, Bull.* **167,** 156–158 (1900).

[3] Steiger, George, The solubility in water of certain natural silicates: *U. S. Geol. Survey, Bull.* **167,** 159–160 (1900).

[4] Atkins, W. R. G., Some geochemical applications of measurements of hydrogen-ion concentration: *Roy. Dublin Soc. Sci. Proc.*, **19,** 455–460 (1930).

[5] Stevens, R. E., Studies on the alkalinity of some silicate minerals: *U. S. Geol. Survey, Prof. Paper* **185A,** 1–13 (1934–1935).

[6] Umegaki, Yosiharu, Über die bei der Hydrolyse der Plagioklase und einiger Karbonatmineralien nachgewiesene Wasserstoffion-Konzentration: *Mem. Coll. Sci., Kyoto Imp. Univ.*, **14,** 141–154 (1938).

$$HA+BOH=BA+H_2O.$$

The salt formed is a combination of elements in simple proportion, and, in the above reaction, the salt (BA) consists of an equal number of atoms of element B and of element A.

The hydrolysis of a salt may be represented as the reverse of the above reaction thus:

$$BA+HOH=HA+BOH.$$

As the acid (HA) and the alkali (BOH) are thus produced in equal molecular quantities the acidity or alkalinity of the resulting solution is dependent upon the extent to which the acid is ionized to yield hydrogen-ions and the alkali is ionized to yield hydroxyl-ions. Representing a strongly ionized acid by HA and a weakly ionized one by Ha, and a strong and a weak alkali by BOH and bOH respectively, the hypothetical salts BA, bA, Ba, and ba hydrolyze as follows:

$BA+HOH \rightleftarrows HA+BOH$ (solution essentially neutral)
$bA+HOH \rightleftarrows HA+bOH$ (solution acid)
$Ba+HOH \rightleftarrows Ha+BOH$ (solution alkaline)
$ba+HOH \rightleftarrows Ha+bOH$ (solution essentially neutral)

As examples of the above types of hydrolysis the following reactions of minerals with water may be cited:

KCl (sylvite) $+HOH \rightleftarrows HCl+KOH$ (solution essentially neutral, pH 6)
$Fe_2(SO_4)_3 \cdot 9H_2O$ (coquimbite) $+HOH \rightleftarrows 3H_2SO_4+2Fe(OH)_3+4H_2O$ (solution acid, pH 1)
$Na_2B_4O_7 \cdot 10H_2O$ (borax) $+HOH \rightleftarrows H_2B_4O_7+2NaOH+9H_2O$ (solution alkaline, pH 10)
$PbCO_3$ (cerussite) $+2HOH \rightleftarrows H_2CO_3+Pb(OH)_2$ (solution essentially neutral, pH 6)

In addition to the above types of materials, there are acid and basic salts whose pH in water is dependent not only upon the ionization of the acids and alkalies formed by hydrolysis but also upon the proportion of acid- or alkali-producing constituents, in the salt. Thus K_2SO_4 is essentially neutral, but $KHSO_4$ has a strong acid reaction. Weak acids and weak bases also occur as minerals, examples being H_3BO_3 (sassolite) and $Al(OH)_3$ (gibbsite), which give essentially neutral reactions in water.

This discussion of the elementary theoretical background of the test shows that the abrasion pH of a mineral may indicate its composition type and identity. Thus a mineral giving an abrasion pH of 2 is generally a salt of a weak alkali and a strong acid. However, other factors which may contribute to the result of the test are hardness and nonreactivity, cleavage in relation to the positions of atoms and impurities.

Many interesting differences in abrasion pH result from the substitution of one element for another in a mineral. Thus pyrophyllite, $Al_2Si_4O_{10}(OH)_2$, gives abrasion pH of 6, while its magnesium analogue talc, $Mg_3Si_4O_{10}(OH)_2$, gives pH 9. Increasing substitution of Li for Al in lepidolite raises the abrasion pH of that mineral.

Procedures for Making Mineral Suspensions for Abrasion pH Determinations.

With streak plate: For soft non-absorbent minerals scratch the mineral in a drop of water* on a streak plate for about a minute to form a milky suspension. Determine the abrasion pH with the appropriate indicator papers.

With mortar and pestle: For hard minerals and those that absorb water, grind fragments of the mineral for a minute with a few drops of water to make a heavy suspension and apply the indicator papers.

pH indicator papers: The abrasion pH may be determined in the laboratory either by the use of indicators in solution or by indicator papers. As indicator papers have obvious advantages for field work, they have been used in the present study.

Extensive lists of pH indicators are given by Clark,[7] Britton,[8] and in the Handbook of Chemistry and Physics[9] of the Chemical Rubber Co. Lange's Handbook of Chemistry[10] gives lists of indicators and an illustrative chart showing the pH ranges of various indicators. In most colorimetric pH work, in which buffer solutions are used for standards of comparison the entire range of color change is used for estimation of pH. In the present study the point at which an indicator changes from one color to another was found to be most useful as indicating a pH above or below a certain value. For example, pyrophyllite (pH 6) changes phenol red paper to yellow, indicating a pH below 6.8, whereas talc (pH 9) turns this indicator red. Other indicators with useful color changes are: thymol blue—red below pH 2.8, yellow above; methyl orange—red below pH 4.4, yellow above; brom thymol blue—yellow below pH 6.0, blue above; methyl red—red below pH 6.3, yellow above; phenol red—yellow below pH 6.8, red above; thymol blue—yellow below pH 8.0, blue above; phenolphthalein—colorless below pH 8.3, red above; alizarin yellow R—yellow below pH 10.1, orange above; Poirrier's blue—blue below pH 11.0, red above.

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* Most of the tests here recorded were made with Washington, D. C., tap water, which is essentially neutral and gave abrasion pH values identical with distilled water. In the field natural waters may be used. Waters of high alkalinity, acidity, or salinity should not be used.

[7] Clark, W. Mansfield, The determination of hydrogen ions, 3rd ed., pp. 76–94, Baltimore, The Williams and Wilkins Company **(1928)**.

[8] Britton, H. T. S., Hydrogen ions, 2nd ed., London, Chapman and Hall **(1932)**.

[9] Handbook of Chemistry and Physics, 29th ed., 1363–1366, Cleveland, Ohio, Chemical Rubber Publishing Co. **(1945)**.

[10] Lange's Handbook of Chemistry, p. 904, Sandusky, Ohio, Handbook Publishers, Inc. **(1937)**.

These indicators may be made up in solution as described by Clark, and strips of filter paper dipped therein and dried.

Prepared indicator papers may be purchased. Accutint papers, prepared by Anachemia, Ltd., Montreal, Canada, have been used extensively in this study. These papers are bound in small booklet form and a color chart for making the estimations is provided. Three wide-range Accutint papers are used for rough estimation and twenty short-range papers allow more precise measurements. pHydrion papers, distributed by Palo-Myers, Inc., New York City, are furnished in a convenient transparent plastic dispenser and consist of 2 wide-range papers covering all pH values, and 6 short-range papers. Nitrazine papers covering the pH range 4.5 to 7.5 are distributed by E. R. Squibb and Sons, New York. These are a few of the many brands of pH indicator papers available.

In using these papers for abrasion pH determinations they are dipped in the mineral suspension and removed to observe the color, mineral particles being retained on the under surface of the paper. Maximum deviation from neutrality is noted in making color comparisons with the chart. Suspensions of many minerals exhibit this maximum deviation on the paper only close to the mineral particles.

Determinations of Abrasion pH of Minerals.

Determinations of abrasion pH of a number of minerals are listed in table 1. In all, 280 minerals have been studied, many of the determinations repeatedly confirmed by results obtained on numerous specimens from different localities. In the table, the minerals giving various abrasion pH values are listed (alphabetically for each pH value), the number of specimens giving the specified values are noted, and abrasion pH values found for other specimens in the present study are given. At the end of the table is an index to the abrasion pH of the various mineral species.

The abrasion pH of minerals has been found to range from pH 1 to pH 12. Many of the mineral species do not vary in abrasion pH from specimen to specimen, whereas others may vary by as much as two or three units. For example, pyrophyllite which is essentially fixed in composition, $Al_2Si_4O_{10}(OH)_2$, gave consistently abrasion pH 6, whereas lepidolite, in which isomorphous substitution of Li for Al is known to occur, gave abrasion pH values of 8 to 9, the higher value representing samples highest in lithium. Biotite, a mineral in which Mg and Fe substitute for each other varied in abrasion pH between 8 and 9, and phlogopite, the magnesium end-member of the series, gave abrasion pH values of 10 and 11.

The abrasion pH of the carbonate minerals of calcium and magnesium should be a useful test for differentiating these minerals in the field. Calcite gives consistently an abrasion pH of around 8, dolomite 9 to 10, and magnesite 10 to 11, thus enabling calcite to be quickly differentiated from these magnesium-containing carbonates. Several indicators are useful for this purpose, the best being phenolphthalein paper. With this indicator paper the abrasion test of calcite gives a colorless reaction (pH below 8.3), whereas dolomite and magnesite give an intense red color. Differentiation between dolomite and magnesite is not as definite, differences in abrasion pH being not as great and the available indicators in that range not as satisfactory.

It was hoped that sufficient differences in abrasion pH would be found to identify the different minerals of the plagioclase feldspar series. However, the calcium end-member, anorthite, $CaAl_2Si_2O_8$, gives an abrasion pH of 8 and the sodium end-member, albite, $NaAlSi_3O_8$, gives values ranging between 9 and 10. The spread in abrasion pH between the two end-members is not wide enough for differentiation of the intermediate plagioclase feldspars.

The differences in abrasion pH are further shown in Fig. 1, illustrating values found for representative minerals. This chart is similar to those published elsewhere to show pH ranges of indicators. The close interdependence of composition to abrasion pH can be readily seen.

The distribution in abrasion pH for the 280 different mineral species tested is illustrated in Fig. 2. Most minerals are nearly neutral or alkaline in reaction.

It is interesting to note that many of the pH groups contain minerals closely associated geologically. Thus minerals giving abrasion pH 1, 2 and 3 are the sulfates commonly formed when the acid solutions from oxidation of pyrite decompose aluminous rocks. Minerals of abrasion pH 10 include numerous borates and a number of minerals found in contact limestones (albite, amphibole, chondrodite, diopside, dolomite, hornblende, idocrase, monticellite, olivine, pectolite, phlogopite, picrolite, prehnite, pyroxene, serpentine, tremolite, and xonotlite). Those of abrasion pH 11 include several rare minerals usually found together, such as hillebrandite, merwinite, thaumasite, spurrite, etc. Soda lime carbonates, which occur together in nature, give abrasion pH 12. In a recent study of the biotite-phlogopite series of micas Heinrich[11] shows that high-

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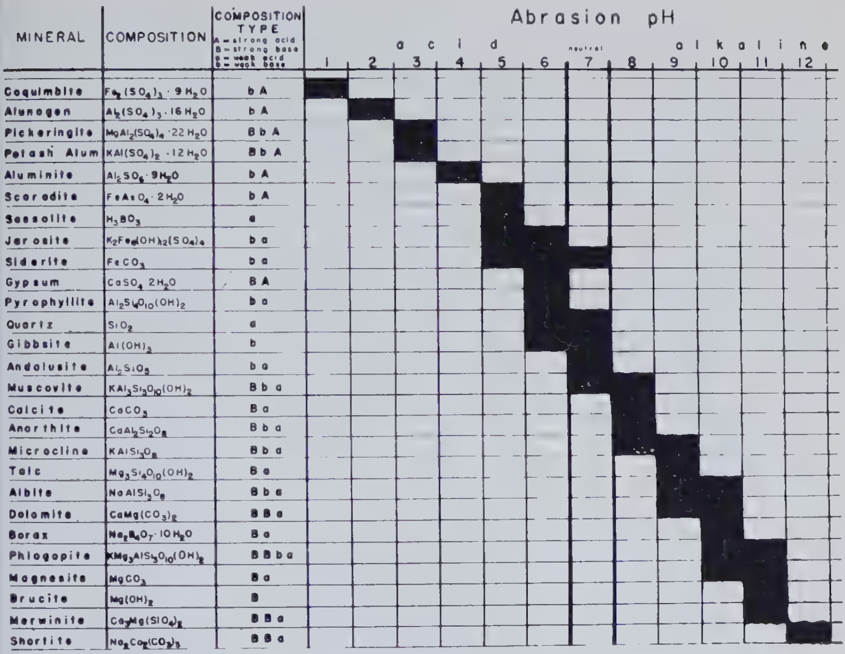
[11] Heinrich, E. Wm., Studies in the mica group; the biotite-phlogopite series: *Am. Jour. Sci.*, **244,** 836–848 (1946).



MINERAL	COMPOSITION	COMPOSITION TYPE A = strong acid B = strong base a = weak acid b = weak base
Coquimbite	$Fe_2(SO_4)_3 \cdot 9H_2O$	b A
Alunogen	$Al_2(SO_4)_3 \cdot 16H_2O$	b A
Pickeringite	$MgAl_2(SO_4)_4 \cdot 22H_2O$	B b A
Potash Alum	$KAl(SO_4)_2 \cdot 12H_2O$	B b A
Aluminite	$Al_2SO_6 \cdot 9H_2O$	b A
Scorodite	$FeAsO_4 \cdot 2H_2O$	b A
Sassolite	H_3BO_3	a
Jarosite	$K_2Fe_6(OH)_{12}(SO_4)_4$	b a
Siderite	$FeCO_3$	b a
Gypsum	$CaSO_4\ 2H_2O$	B A
Pyrophyllite	$Al_2Si_4O_{10}(OH)_2$	b a
Quartz	SiO_2	a
Gibbsite	$Al(OH)_3$	b
Andalusite	Al_2SiO_5	b a
Muscovite	$KAl_3Si_3O_{10}(OH)_2$	B b a
Calcite	$CaCO_3$	B a
Anorthite	$CaAl_2Si_2O_8$	B b a
Microcline	$KAlSi_3O_8$	B b a
Talc	$Mg_3Si_4O_{10}(OH)_2$	B a
Albite	$NaAlSi_3O_8$	B b a
Dolomite	$CaMg(CO_3)_2$	B B a
Borax	$Na_2B_4O_7 \cdot 10H_2O$	B a
Phlogopite	$KMg_3AlSi_3O_{10}(OH)_2$	B B b a
Magnesite	$MgCO_3$	B a
Brucite	$Mg(OH)_2$	B
Merwinite	$Ca_3Mg(SiO_4)_2$	B B a
Shortite	$Na_2Ca_2(CO_3)_3$	B B a

FIG. 1. Abrasion pH values of representative minerals.

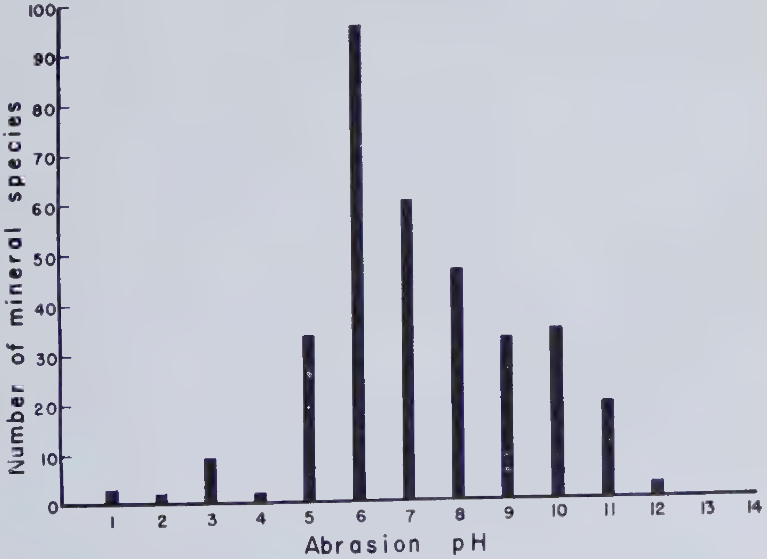


FIG. 2. Abrasion pH distribution of mineral species tested.

iron biotites are associated with the less basic rocks, such as granitic pegmatites, granites, etc., while phlogopites are found in more basic rocks, such as gabbro, peridotite and other ultramafics, and metamorphosed limestones. This occurrence together of minerals of equal abrasion pH is probably not as common for minerals of igneous origin as for those formed in hydrous environments.

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ABRASION pH OF MINERALS

	Mineral	*Composition*	*Number of specimens*	*Other abrasion pH values*
pH 1	Coquimbite	$Fe_2(SO_4)_3 \cdot 9H_2O$	1	
	Kornelite	$Fe_2(SO_4)_3 \cdot 7\frac{1}{2}H_2O$	1	
	Rhomboclase	$FeH(SO_4)_2 \cdot 4H_2O$	1	
pH 2	Alunogen	$Al_2(SO_4)_3 \cdot 16H_2O$	1	
	Melanterite	$FeSO_4 \cdot 7H_2O$	1	3
pH 3	Alum	$KAl(SO_4)_2 \cdot 12H_2O$	2	
	Botryogen	$Mg_2Fe_2(SO_4)_4(OH)_2 \cdot 14H_2O$	1	
	Copiapite	$Fe_4(OH)_2(SO_4)_5 \cdot 18H_2O$	1	
	Halotrichite	$FeAl_2(SO_4)_4 \cdot 22H_2O$	1	
	Melanterite	$FeSO_4 \cdot 7H_2O$	1	2
	Pickeringite	$MgAl_2(SO_4)_4 \cdot 22H_2O$	9	
	Redingtonite	$(Fe, Mg)(Al, Cr)_2(SO_4)_4 \cdot 22H_2O$	2	
	Tschermigite	$NH_4Al(SO_4)_2 \cdot 12H_2O$	2	
	Vanoxite	$2V_2O_4 \cdot V_2O_5 \cdot 8H_2O$	1	
pH 4	Aluminite	$Al_2SO_6 \cdot 9H_2O$	1	
	Turquois	$H_5(CuOH)[Al(OH)_2]_6(PO_4)_4$	1	6
pH 5	Anglesite	$PbSO_4$	2	
	Blomstrandite	Titanocolumbate of U, Th, Y, Er, Ce, etc.	1	
	Carnallite	$KMgCl_3 \cdot 6H_2O$	1	
	Celestite	$SrSO_4$	2	6
	Cotunnite (art.)	$PbCl_2$	1	
	Cyrtolite	Altered $ZrSiO_4$	2	6, 7
	Diadochite	Basic iron sulfate-phosphate	2	
	Evansite	$2AlPO_4 \cdot 4Al(OH)_3 \cdot 12H_2O$	1	
	Glauconite	$K_2(Mg, Fe)_2Al_6(Si_4O_{10})_3(OH)_2$	1	
	Jarosite	$K_2Fe_6(OH)_{12}(SO_4)_4$	4	6
	Kaolinite	$Al_2Si_2O_5(OH)_4$	1	6, 7
	Minervite	Hydrous phosphate of K and Al	1	

	Mineral	*Composition*	*Number of specimens*	*Other abrasions pH value*
	Monazite	Essentially (Ce, La, Pr, Nd)PO_4	2	6
	Nontronite	$FeSi_2O_5(OH) \cdot nH_2O$	2	6
	Paligorskite	Hydrous Mg Al silicate	1	7
	Plumbojarosite	$PbFe_6(OH)_{12}(SO_4)_4$	1	
	Polyhalite	$2CaSO_4 \cdot MgSO_4 \cdot K_2SO_4 \cdot 2H_2O$	2	6
	Pseudoboléite	$5PbCl_2 \cdot 4CuO \cdot 6H_2O$	1	
	Pseudowavellite	$CaAl_3(PO_4)_2(OH)_5 \cdot H_2O$	1	
	Rectorite	Appx. $NaAl_5Si_7O_{20}(OH)_4 \cdot 4H_2O$	1	
	Rhagite	$2BiAsO_4 \cdot 3Bi(OH)_3$	1	
	Sassolite	H_3BO_3	3	
	Scorodite	$FeAsO_4 \cdot 2H_2O$	2	
	Siderite	$FeCO_3$	1	6, 7
	Spencerite	$Zn(PO_4)_2 \cdot Zn(OH)_2 \cdot 3H_2O$	1	
	Sphalerite	ZnS	1	6
	Staurolite	$FeAl_4Si_2O_{10}(OH)_2$	1	6, 7
	Stibiotantalite	$Sb_2(Ta, Cb)_2O_8$	1	
	Uraninite (pitchblende)	UO_2	1	6
	Vanadinite	$3Pb_3V_2O_8 \cdot PbCl_2$	2	6
	Variscite	$AlPO_4 \cdot 2H_2O$	1	6
	Vivianite	$Fe_3P_2O_8 \cdot 8H_2O$	2	
	Wavellite	$4AlPO_4 \cdot 2Al(OH)_3 \cdot 9H_2O$	1	
pH 6	Alunite	$KAl_6(OH)_{12}(SO_4)_4$	5	
	Anhydrite	$CaSO_4$	4	
	Arseniosiderite	$Ca_3Fe(AsO_4)_3 \cdot 3Fe(OH)_3$	1	
	Barite	$BaSO_4$	1	
	Bastnaesite	(Ce, La, Pr, Nd)FCO_3	1	
	Beaverite	$CuO \cdot PbO \cdot Fe_2O_3 \cdot 2SO_3 \cdot 4H_2O$	1	
	Beryl	$Be_3Al_2Si_6O_{18}$	6	7
	Betafite	Titanocolumbate of U, etc.	6	
	Bismutite	$Bi_2CO_5 \cdot H_2O$	1	
	Bloedite	$MgSO_4 \cdot Na_2SO_4 \cdot 4H_2O$	1	
	Boehmite	AlO(OH)	1	7
	Boléite	$9PbCl_2 \cdot 8CuO \cdot 3AgCl \cdot 9H_2O$	1	
	Brookite	TiO_2	1	
	Cassiterite	SnO_2	2	
	Celestite	$SrSO_4$	2	5
	Cerussite	$PbCO_3$	1	
	Chrysoberyl	$BeAl_2O_4$	1	7
	Chrysocolla	$CuSiO_3 \cdot 2H_2O$	1	
	Columbite	(Fe, Mn)(Cb, Ta)$_2$O$_6$	1	
	Cryolite	Na_3AlF_6	1	7
	Cuprotungstite	$Cu_2WO_5 \cdot H_2O$	1	
	Cyrtolite	Altered $ZrSiO_4$	1	5, 7
	Descloisite	$PbZnVO_4(OH)$	1	
	Diaspore	$HAlO_2$	3	7
	Dickite	$Al_2Si_2O_5(OH)_4$	7	

Mineral	*Composition*	*Number of specimens*	*Other abrasion pH values*
Dumortierite	$Al_8BSi_3O_{19}(OH)$	4	7
Eosphorite	$AlPO_4 \cdot Mn(OH)_2 \cdot H_2O$	1	
Euxenite	Columbate and titanothorate of Y, Er, Ce, U	1	
Fayalite	Fe_2SiO_4	1	
Flajolotite	$4FeSbO_4 \cdot 3H_2O$	1	
Francolite	$3Ca_3P_2O_8 \cdot Ca[F_2, (OH)_2, CO_3]$	1	7
Fremontite	$(Na, Li)Al(OH, F)PO_4$	1	
Gibbsite	$Al(OH)_3$	1	7
Glauberite	$Na_2SO_4 \cdot CaSO_4$	2	
Greenalite	Hydrous ferrous silicate	1	
Gypsum	$CaSO_4 \cdot 2H_2O$	12	
Halite	NaCl	9	
Halloysite	$Al_2Si_2O_5(OH)_4+H_2O$	4	
Hematite	Fe_2O_3	1	
Hemimorphite	$Zn_2SiO_3(OH)_2$	2	7
Herderite	$CaBe(F, OH)PO_4$	1	
Hinsdalite	$2PbO \cdot 3Al_2O_3 \cdot P_2O_5 \cdot 2SO_3 \cdot 6H_2O$	1	
Huebnerite	$MnWO_4$	3	
Hureaulite	$H_2Mn_5(PO_4)_4 \cdot 4H_2O$	1	
Ilmenite	$FeTiO_3$	2	
Ilmenorutile	$TiO_2 \cdot nFe(Cb, Ta)_2O_6$	1	
Jarosite	$K_2Fe_6(OH)_{12}(SO_4)_4$	1	5
Kaolinite	$Al_2Si_2O_5(OH)_4$	1	5, 7
Kieserite	$MgSO_4 \cdot H_2O$	1	
Kyanite	Al_2SiO_5	4	
Langbeinite	$K_2Mg_2(SO_4)_3$	1	
Lanthanite	$(La, Pr, Nd, Ce)_2(CO_3)_3 \cdot 8H_2O$	1	
Lepidocrocite	$FeO(OH)$	1	
Manganotantalite	$(Fe, Mn)(Cb, Ta)_2O_6$	1	
Mirabilite	$Na_2SO_4 \cdot 10H_2O$	1	
Monazite	$(Ce, La, Pr, Nd)PO_4$	1	5
Montmorillonite	$(Al_2, Mg_3)Si_4O_{10}(OH)_2 \cdot nH_2O$	2	7
Montmorillonite (Bentonite)	Ditto	2	
Mottramite	$PbCuVO_4(OH)$	2	
Nitre	KNO_3	2	
Nitrocalcite	$Ca(NO_3)_2 \cdot 4H_2O$	1	
Nontronite	$FeSi_2O_5(OH) \cdot nH_2O$	3	5
Olivenite	$Cu_3As_2O_8 \cdot Cu(OH)_2$	1	
Opal	$SiO_2 \cdot nH_2O$	1	7
Pinite	Near muscovite	1	
Planchéite	$3CuSiO_3 \cdot H_2O$	1	
Polyhalite	$2CaSO_4 \cdot MgSO_4 \cdot K_2SO_4 \cdot 2H_2O$	1	5
Pyrophyllite	$Al_2Si_4O_{10}(OH)_2$	9	
Quartz	SiO_2	1	7
Quartz (amethyst)	SiO_2	1	7

	Mineral	*Composition*	*Number of specimens*	*Other abrasion pH values*
	Reddingite	$Mn_3P_2O_8 \cdot 3H_2O$	1	
	Rhodochrosite	$MnCO_3$	1	7
	Rutile	TiO_2	1	7
	Salammoniac	NH_4Cl	1	
	Samarskite	(Y, Er, Ce, U, Ca, Fe, Pb, Th) $(Cb, Ta, Ti, Sn)_2O_6$	4	
	Scheelite	$CaWO_4$	3	7
	Siderite	$FeCO_3$	2	5, 7
	Soda nitre	$NaNO_3$	1	
	Sphalerite	ZnS	1	5
	Staurolite	$FeAl_4Si_2O_{10}(OH)_2$	2	5, 7
	Sulfur	S	1	
	Sylvite	KCl	2	
	Tantalite	$(Fe, Mn)(Cb, Ta)_2O_6$	1	
	Thorotungstite	W and Th oxides	1	
	Topaz	$Al_2SiO_4(F, OH)_2$	1	7
	Torbernite	$Cu(UO_2)_2P_2O_8 \cdot 8H_2O$	1	
	Triplite	$(Fe, Mn, Mg)PO_4F$	1	
	Tungstite	$WO_3 \cdot H_2O$	1	
	Turquois	$H_5(CuOH)[Al(OH)_2]_6(PO_4)_4$	2	4
	Uraninite (pitchblende)	UO_2	2	5
	Vanadinite	$3Pb_3V_2O_8 \cdot PbCl_2$	1	5
	Vanthoffite	$3Na_2SO_4 \cdot MgSO_4$	1	
	Variscite (lucinite)	$AlPO_4 \cdot 2H_2O$	1	5
	Wolframite	$(Fe, Mn)WO_4$	1	
	Wulfenite	$PbMoO_4$	1	
	Zircon	$ZrSiO_4$	2	
pH 7	Allanite	$(Ca, Ce, La, Na)_2(Al, Fe, Mn, Be, Mg)_3(SiO_4)_3OH$	2	8
	Andalusite	Al_2SiO_5	4	
	Annabergite	$Ni_3As_2O_8 \cdot 8H_2O$	1	
	Aurichalcite	$2(Zn, Cu)CO_3 \cdot 3(Zn, Cu)(OH)_2$	1	
	Azurite	$2CuCO_3 \cdot Cu(OH)_2$	1	
	Beidellite	Similar to montmorillonite	1	
	Beryl	$Be_3Al_2Si_6O_{18}$	6	6
	Boehmite	$AlO(OH)$	1	6
	Brushite (art.)	$HCaPO_4 \cdot 2H_2O$	1	
	Carnotite	$K_2(UO_2)_2(VO_4)_2 \cdot 8H_2O$	1	
	Cerite	$(Ce, Y, Pr, Nd)_2Si_2O_7 \cdot H_2O$	1	
	Chlorite	$(Mg, Fe)_5Al_2Si_3O_{10}(OH)_8$ (var.)	2	8
	Chloritoid	$(Fe, Mg)_2Al_4Si_2O_{10}(OH)_4$ (var.)	1	
	Chrysoberyl	$BeAl_2O_4$	1	6
	Collophanite	$3Ca_3P_2O_8 \cdot Ca[F_2, (OH)_2, CO_3]$	1	
	Corundum	Al_2O_3	1	
	Cryolite	Na_3AlF_6	1	6
	Cyrtolite	Altered $ZrSiO_4$	1	5, 6

Mineral	*Composition*	*Number of specimens*	*Other abrasion pH values*
Danalite	$(Fe, Mn, Zn)_4Be_3Si_3O_{12}S$	2	
Diaspore	$HAlO_2$	1	6
Dickinsonite	$H_2Na(Mn, Fe)_{14}(PO_4)_{12} \cdot H_2O$	1	
Dumortierite	$Al_8BSi_3O_{19}(OH)$	3	6
Fairfieldite	$Ca_2MnP_2O_8 \cdot 2H_2O$	2	
Fillowite	$3(Mn, Fe, Na_2)_3P_2O_8 \cdot H_2O$	1	
Fluorite	CaF_2	5	
Francolite	$3Ca_3P_2O_8 \cdot Ca[F_2, (OH)_2, CO_3]$	1	6
Fuchsite	$K(Al, Cr)_2AlSi_3O_{10}(OH)_2$	2	
Gahnite	$ZnAl_2O_4$	1	
Garnet	$(Mg, Fe^{++}, Mn^{++}, Ca)_3(Al, Fe^{+++}, Cr, Ti, Mn^{+++})_2(SiO_4)_3$	3	
Gearksutite	$CaF_2 \cdot Al(F, OH)_3 \cdot H_2O$	1	
Gibbsite	$Al(OH)_3$	1	6
Grunerite	$(Mn, Fe, Mg)Si_8O_{22}(OH)_2$	1	
Hambergite	$Be_2(OH)BO_3$	1	
Helvite	$(Mn, Fe, Zn)_4Be_3Si_3O_{12}S$	1	
Hemimorphite	$Zn_2SiO_3(OH)_2$	4	6
Hulsite	$Fe_4^{++}Fe_2^{+++}B_2O_{10}$ with Mg and Sn	1	
Kaolinite	$Al_2Si_2O_5(OH)_4$	1	5, 6
Malachite	$CuCO_3 \cdot Cu(OH)_2$	1	
Montmorillonite	$(Al_2, Mg_3)Si_4O_{10}(OH)_2 \cdot nH_2O$	3	6
Muscovite (sericite)	$KAl_3Si_3O_{10}(OH)_2$	1	8
Opal	$SiO_2 \cdot nH_2O$	1	6
Paligorskite	Hydrous MgAl silicate	1	5
Parsettensite	$Mn_4Si_4O_{10}(OH)_4 \cdot 3H_2O$	1	
Petalite	$LiAlSi_4O_{10}$	2	8
Pyroxmangite	$(Mn, Fe)SiO_3$	1	
Quartz	SiO_2	1	6
Quartz (amethyst)	SiO_2	1	6
Rhodochrosite	$MnCO_3$	1	6
Rutile	TiO_2	1	6
Scapolite	$(Na, Ca)_8Al_6(Al, Si)_6Si_{12}O_{48}(Cl_2, CO_3)$	1	8
Scheelite	$CaWO_4$	1	6
Siderite	$FeCO_3$	2	5, 6
Sillimanite	Al_2SiO_5	3	
Smithsonite	$ZnCO_3$	1	
Spinel	$MgAl_2O_4$	1	
Staurolite	$FeAl_4Si_2O_{10}(OH)_2$	1	5, 6
Stilbite	$(Ca, Na, K)_3Al_5(Al, Si)Si_{14}O_{40} \cdot 15H_2O$	1	8
Strontianite	$SrCO_3$	1	8
Thenardite	Na_2SO_4	1	
Thorianite	$(Th, U)O_2$	1	
Topaz	$Al_2SiO_4(F, OH)_2$	2	6
Tourmaline	$(Na, Ca)(Mg, Fe^{++}, Fe^{+++})_3B_3Al_3(Al_3Si_6O_{27})(O, OH)_4$	5	8
Triploidite	$(Fe, Mn)OH \cdot (Fe, Mn)PO_4$	1	

	Mineral	*Composition*	*Number of specimens*	*Other abrasion pH values*
pH 8	Allanite	$(Ca, Ce, La, Na)_2(Al, Fe, Mn, Be, Mg)_3(SiO_4)_3OH$	1	7
	Amblygonite	$LiAl(F, OH)PO_4$	1	
	Anorthite	$CaAl_2Si_2O_8$	1	
	Anthophyllite	$(Mg, Fe)_7Si_8O_{22}(OH)_2$	5	9
	Apatite	$Ca_3P_2O_8 \cdot Ca[F_2, Cl_2, (OH)_2, O, CO_3, SO_4]$	6	
	Aragonite	$CaCO_3$	3	
	Bementite	$Mn_5Si_4O_{10}(OH)_6$	1	9
	Benitoite	$BaTiSi_3O_9$	1	
	Biotite	$K(Mg, Fe)_3AlSi_3O_{10}(OH)_2$	3	9
	Calcite	$CaCO_3$	16	
	Chlorite	$(Mg, Fe)_5Al_2Si_3O_{10}(OH)_8$ (var.)	2	7
	Chondrodite	$Mg_5(SiO_4)_2(F, OH)_2$	1	10
	Cryophyllite	$K_2Fe_2^{++}Li_3Al_3Si_7O_{20}(OH, F)_4$	1	
	Epidote	$Ca_2(Al, Fe)_3Si_3O_{12}(OH)$	5	
	Gillespite	$BaFeSi_4O_{10}$	1	
	Hectorite	Li, Mg end-member montmorillonite	1	
	Heulandite	$(Ca, Na, K)_6Al_{10}(Al, Si)Si_{29}O_{80} \cdot 25H_2O$	1	
	Hypersthene	$(Fe, Mg)SiO_3$	1	
	Labradorite	$Ab_{50-30}An_{50-70}$	2	9
	Larderellite	$(NH_4)_2B_{10}O_{16} \cdot 5H_2O$	1	
	Lawsonite	$CaAl_2Si_2O_7(OH)_2 \cdot H_2O$	1	
	Lepidolite	Lithium mica	5	9
	Lithiophyllite	$Li(Mn, Fe)PO_4$	2	
	Ludwigite	$Mg_4Fe_2B_2O_{10}$	1	
	Margarite	$CaAl_4Si_2O_{10}(OH)_2$	3	9
	Microcline	$KAlSi_3O_8$	4	9
	Muscovite	$KAl_3Si_3O_{10}(OH)_2$	7	7
	Nahcolite	$NaHCO_3$	1	
	Orthoclase	$KAlSi_3O_8$	6	
	Petalite	$LiAlSi_4O_{10}$	1	7
	Phillipsite	$(Ca, Ba, K, Na)_3Al_4(Al, Si)Si_5O_{20} \cdot 10H_2O$	1	
	Pollucite	$(Cs, Na, K)_4(Si, Al)_{13}O_{26} \cdot H_2O$	6	
	Rhodonite	$MnSiO_3$	3	
	Roscoelite	$KV_2AlSi_3O_{10}(OH)_2$ (var.)	1	
	Scapolite	$(Na, Ca)_8Al_6(Al, Si)_6Si_{12}O_{48}(Cl_2, CO_3)$	3	7
	Scolecite	$CaAl_2Si_3O_{10} \cdot 3H_2O$	1	
	Sepiolite	$Mg_2Si_3O_6(OH)_4$	1	
	Serpentine (ferruginous)	$(Mg, Fe)_3Si_2O_5(OH)_4$	1	10
	Spodumene	$LiAlSi_2O_6$	2	
	Stilbite	$(Ca, Na, K)_3Al_5(Al, Si)Si_{14}O_{40} \cdot 15H_2O$	2	7
	Strontianite	$SrCO_3$	1	7
	Tourmaline	$(Na, Ca)(Mg, Fe^{++}, Fe^{+++})_3B_3Al_3(Al_3Si_6O_{27})(O, OH)_4$	1	7
	Vermiculite	$(Mg, Fe)_3(Al, Fe)AlSi_3O_{10}(OH)_4 \cdot 4H_2O$	1	9
	Witherite	$BaCO_3$	1	

	Mineral	*Composition*	*Number of specimens*	*Other abrasion pH values*
	Zincite	ZnO	1	
	Zinnwaldite	$KLiMgAl_2Si_3O_{10}(OH, F)_2$	3	
pH 9	Aegirite	$(Ca, Na)(Mg, Fe, Al)Si_2O_6$	3	
	Albite	$NaAlSi_3O_8$	1	10
	Albite (peristerite)	Ditto	1	
	Alleghenyite	$Mn_5(SiO_4)_2(OH, F)_2$	1	
	Anthophyllite	$(Mg, Fe)_7Si_8O_{22}(OH)_2$	4	8
	Bavenite	$Ca_4BeAl_2Si_9O_{25}(OH)_2$	1	
	Bementite	$Mn_5Si_4O_{10}(OH)_6$	3	8
	Biotite	$K(Mg, Fe)_3AlSi_3O_{10}(OH)_2$	1	8
	Chabazite	$(Ca, Na, K)_7Al_{12}(Al, Si)_2Si_{26}O_{80} \cdot 40H_2O$	1	
	Chlorite (sheridanite)	$Mg_5Al_2Si_3O_{10}(OH)_8$	1	
	Clinochlore	$(Mg, Fe)_5Al_2Si_3O_{10}(OH)_8$	2	
	Colemanite	$Ca_2B_6O_{11} \cdot 5H_2O$	1	10
	Danburite	$CaB_2Si_2O_8$	1	
	Deweylite	$4MgO \cdot 3SiO_2 \cdot 6H_2O$	1	
	Dolomite	$CaMg(CO_3)_2$	1	10
	Idocrase	$Ca_{10}Al_4(Mg, Fe)_2Si_9O_{34}(OH)_4$	3	10
	Imerinite	Sodium amphibole	1	
	Inyoite	$2CaO \cdot 3B_2O_3 \cdot 13H_2O$	1	
	Kotschubeite	$(Mg, Fe)_5Al_2Si_3O_{10}(OH)_8$	1	
	Labradorite	$Ab_{50-30}An_{50-70}$	2	8
	Lepidolite	Lithium mica	3	8
	Margarite	$CaAl_4Si_2O_{10}(OH)_2$	1	8
	Microcline	$KAlSi_3O_8$	4	8
	Oligoclase	$Ab_{90-70}An_{10-30}$	3	
	Polylithionite	$KLi_2AlSi_4O_{10}F_2$	1	
	Serendibite	$CaMg_2Al_3BSi_2O_{13}$	1	
	Sphene	$CaTiSiO_5$	3	
	Talc	$Mg_3Si_4O_{10}(OH)_2$	5	
	Ulexite	$NaCaB_5O_9 \cdot 8H_2O$	2	10
	Vermiculite	$(Mg, Fe)_3(Al, Fe)AlSi_3O_{10}(OH)_4 \cdot 4H_2O$	1	8
	Xanthophyllite (walueite)	$CaMg_2Al_4SiO_{10}(OH)_2$	1	
	Zoisite	$Ca_2Al_3Si_3O_{12}(OH)$	8	
pH 10	Albite	$NaAlSi_3O_8$	2	9
	Amphibole	$(Mg, Fe, Ca, Al)_7(Si, Al)_8O_{22}(OH, F)_2$	1	
	Augite	$Ca(Mg, Fe, Al)(Al, Si)_2O_6$	3	
	Borax	$Na_2B_4O_7 \cdot 10H_2O$	1	
	Chondrodite	$Mg_5(SiO_4)_2(F, OH)_2$	1	8
	Colemanite	$Ca_2B_6O_{11} \cdot 5H_2O$	3	9
	Datolite	$CaBSiO_4(OH)$	3	11
	Diopside	$CaMgSi_2O_6$	6	11
	Diopside (violane)	Ditto	1	
	Dolomite	$CaMg(CO_3)_2$	2	9

	Mineral	*Composition*	*Number of specimens*	*Other abrasion pH values*
	Hornblende	$Ca_2Na(Mg, Fe^{++})_4(Al, Fe^{+++}, Ti)_3Si_6O_{22}(O, OH)_2$	1	
	Howlite	$Ca_2SiB_5O_9(OH)_5$	3	
	Idocrase	$Ca_{10}Al_4(Mg, Fe)_2Si_9O_{34}(OH)_4$	4	9
	Inesite	$Mn_7Ca_2Si_{10}O_{28}(OH)_2 \cdot 5H_2O$	1	
	Jeffersonite	$Ca(Mg, Mn, Fe, Zn)Si_2O_6$	1	
	Kernite	$Na_2B_4O_7 \cdot 4H_2O$	1	
	Leucite	$(Ca, Na, K)(Al, Si)_2O_6$	1	
	Magnesite	$MgCO_3$	1	11
	Monticellite	$CaMgSiO_4$	1	
	Natrolite	$Na_2Al_2Si_3O_{10} \cdot 2H_2O$	3	
	Nesquehonite	$MgCO_3 \cdot 3H_2O$	1	
	Olivine (chrysolite)	$(Mg, Fe)_2SiO_4$	1	11
	Pectolite	$Ca_2NaSi_3O_8(OH)$	1	11
	Phlogopite	$KMg_3AlSi_3O_{10}(OH)_2$	5	11
	Prehnite	$Ca_2Al_2Si_3O_{10}(OH)_2$	2	
	Pyroxene	$(Ca, Mg, Fe, Mn, Zn)SiO_3$	1	
	Roweite	$H_2(Mn, Mg, Zn)Ca(BO_3)_2$	1	
	Searlesite	$NaB(SiO_3)_2 \cdot H_2O$	1	
	Serpentine	$Mg_3Si_2O_5(OH)_4$	2	8
	Serpentine (picrolite)	Ditto	1	
	Sodalite	$Na_4Al_3Si_3O_{12}Cl$	3	
	Szaibelyite	$Mg_2B_2O_5 \cdot H_2O$	2	
	Tremolite	$Ca_2Mg_5(OH)_2(Si_4O_{11})_2$	1	11
	Trona	$Na_2CO_3 \cdot NaHCO_3 \cdot 2H_2O$	1	
	Ulexite	$NaCaB_5O_9 \cdot 8H_2O$	2	9
	Xonotlite	$Ca_3Si_3O_8(OH)_2$	1	11
	Zeophyllite	$Ca_8Si_6O_{15}(OH, F)_{10}$	1	
pH 11	Actinolite	$Ca_2(Mg, Fe)_5Si_8O_{22}(OH)_2$	4	
	Apophyllite	$KCa_4Si_4O_{10}F_2 \cdot 8H_2O$	3	
	Bakerite	$Ca_8B_{10}Si_6O_{35} \cdot 6H_2O$	1	
	Brucite	$Mg(OH)_2$	3	
	Datolite	$CaBSiO_4(OH)$	1	10
	Diopside	$CaMgSi_2O_6$	1	10
	Hanksite	$9Na_2SO_4 \cdot 2Na_2CO_3 \cdot KCl$	1	
	Hillebrandite	$Ca_2SiO_3(OH)_2$	1	
	Magnesite	$MgCO_3$	3	10
	Merwinite	$Ca_3Mg(SiO_4)_2$	1	
	Olivine	$(Mg, Fe)_2SiO_4$	5	10
	Pectolite	$Ca_2NaSi_3O_8(OH)$	2	10
	Phlogopite	$KMg_3AlSi_3O_{10}(OH)_2$	2	10
	Roeblingite	$2PbSO_4 \cdot Ca_7Si_6O_{14}(OH)_{10}$	1	
	Spurrite	$2Ca_2SiO_4 \cdot CaCO_3$	1	
	Thaumasite	$CaSiO_3 \cdot CaCO_3 \cdot CaSO_4 \cdot 15H_2O$	3	
	Tremolite	$Ca_2Mg_5(OH)_2(Si_4O_{11})_2$	5	10

	Mineral	*Composition*	*Number of specimens*	*Other abrasion pH values*
pH 12	Wollastonite	$CaSiO_3$	5	
	Xonotlite	$Ca_3Si_3O_8(OH)_2$	1	10
	Gaylussite	$CaCO_3 \cdot Na_2CO_3 \cdot 5H_2O$	1	
	Pirssonite	$CaCO_3 \cdot Na_2CO_3 \cdot 2H_2O$	1	
	Shortite	$Na_2Ca_2(CO_3)_2$	1	

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REHYDRATION AND DEHYDRATION OF THE CLAY MINERALS†

Ralph E. Grim and W. F. Bradley*

Abstract

Certain clay minerals, particularly the illites and montmorillonites, regain some hydroxyl water as well as adsorbed water on standing at room temperature after being dehydrated by heating to temperatures as high as 800°C. The removal of the recombined hydroxyl water may take place at slightly lower temperature than the original hydroxyl water.

Experimental data are presented showing the rehydration and loss again of the rehydration water together with a discussion of the structural significance of the rehydration.

Introduction

In the course of the study of the character and properties of the clay minerals as revealed by differential thermal analyses, it was found that certain of the clay minerals apparently rehydrate after being dehydrated by heating to temperatures as high as 800°C. The rehydration includes both the picking up of adsorbed water and the recovery of actual lattice water hydroxyl groups. In the latter case removal of the recombined hydroxyl water may take place at a slightly lower temperature than did the removal of the original hydroxyl water. Dehydration and rehydration are important in considering the properties and the structure of the clay minerals, and may be of practical significance in the utilization of clays. The purpose of the present paper is to present some preliminary work on these matters.

Procedure

About 5 grams of minus 60-mesh material of various clay minerals were heated to temperatures up to 800°C. The samples were heated rapidly to the top temperatures and held there for at least one hour. After heating, the samples were allowed to cool to room temperature (25° to 30°C.) and kept in open dishes, but protected from dust, in the laboratory until they were studied.

The method of study was that of differential thermal analysis (1). This method is satisfactory because dehydration is accompanied by an endothermic reaction. Thermal curves, therefore, indicate any rehydration, the temperature at which the rehydrated water can be removed, and something of the energy involved.

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* Petrographer and Chemist, respectively, Illinois Geological Survey, Urbana, Illinois.

EXPERIMENTAL RESULTS

Montmorillonite

Figure 1 presents thermal curves for a sodium montmorillonite from Wyoming bentonite, obtained on samples which had remained in the laboratory for various periods of time following heating to 500°C., 600°C., and 800°C. for one hour.

Curve B shows that a considerable amount of adsorbed water is picked up in 13 days by material heated to 500°C. This temperature is not high enough to affect the (OH) lattice water.

Heating to 600°C. for one hour (curves C–F) removes the (OH) lattice water as well as the adsorbed water. Following heating to this temperature, there is a very slow gradual pickup of adsorbed water so that a small amount is shown at the end of 268 days. Likewise there is a very slow gradual regaining of (OH) lattice water, and of great interest is the dual character of the endothermic reactions corresponding to the removal of this rehydrated water. Apparently the regained water is of two kinds or forms in the lattice. Some of this water is removed at about the same temperature as the original dehydration, and the other at about 150°C. lower temperature. Both kinds or forms of water are regained at about the same rate.

The samples heated to 800°C. (curves G–H) show no pickup of adsorbed water and only a faint trace of (OH) lattice water regained after 268 days.

The thermal reactions at about 875° to 950°C., corresponding to the destruction of the montmorillonite lattice and the development of new phases (2), are unchanged in samples heated to 600°C. In the 800°C. sample, the only effect is a very slight reduction in the intensity of the reactions.

Figure 2 shows thermal curves obtained on samples of a calcium montmorillonite from an Arizona bentonite, which had remained in the laboratory for various periods of time following heating to 500°, 600°, and 800°C. for one hour.

The curves show that this calcium montmorillonite has the same rehydration characteristics as the sodium montmorillonite shown in Fig. 1, except that the rehydration following heating to 600°C. (curves C–E) seems to be a little slower. The calcium montmorillonite that was heated to 800°C., after standing for 272 days (curve H), definitely shows some pickup of adsorbed water and of (OH) lattice water.

Illite

Differential thermal curves for an illite (3) purified from an underclay of Pennsylvanian age found near Fithian, Illinois, are presented in Fig. 3.

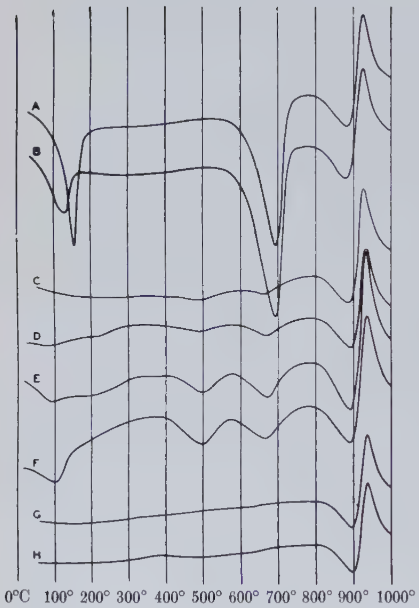


Fig. 1

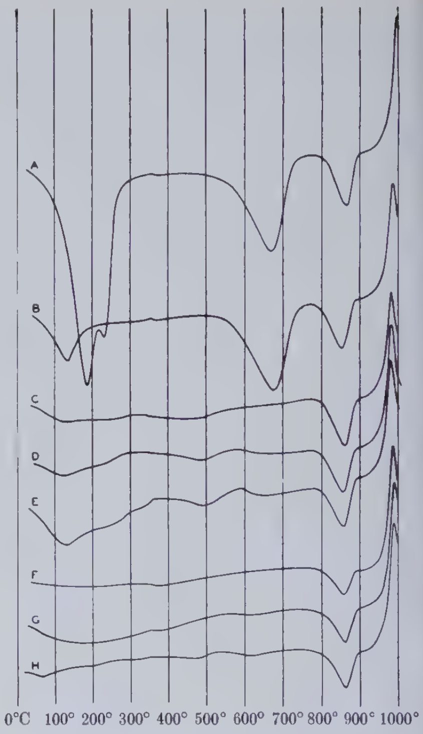


Fig. 2

Fig. 1. Differential thermal curves of sodium montmorillonite, bentonite, Clay Spur, Wyoming.

A. Not heated.
B. Heated 500° C. for 1 hour, curve run after standing 13 days.
C. " 600° C. " 1 " " " " " 11 "
D. " 600° C. " 1 " " " " " 68 "
E. " 600° C. " 1 " " " " " 146 "
F. " 600° C. " 1 " " " " " 268 "
G. " 800° C. " 1 " " " " " 76 "
H. " 800° C. " 1 " " " " " 268 "

Figure 2. Differential thermal curves of calcium montmorillonite, bentonite, Arizona.

A. Not heated.
B. Heated 500° C. for 1 hour, curve run after standing 13 days.
C. " 600° C. " 1 " " " " " 14 "
D. " 600° C. " 1 " " " " " 68 "
E. " 600° C. " 1 " " " " " 145 "
F. " 800° C. " 1 " " " " " 73 "
G. " 800° C. " 1 " " " " " 145 "
H. " 800° C. " 1 " " " " " 272 "

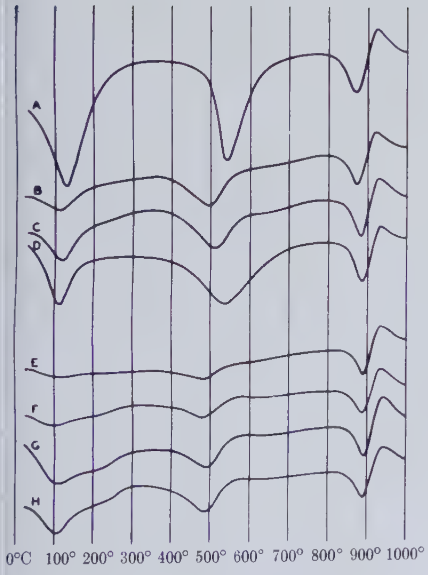


FIG. 3

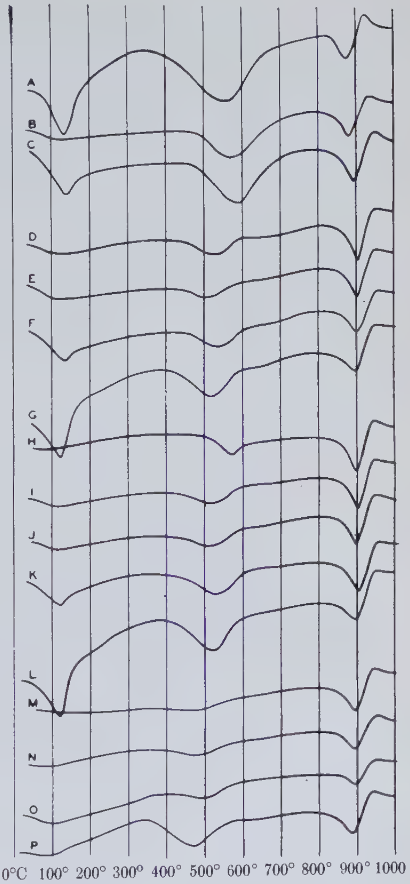


FIG. 4

FIG. 3. Differential thermal curves of illite, Fithian, Illinois.

A. Not heated.
B. Heated 600° C. for 3 hours, curve run after standing 2 hours.
C. " 600° C. " 1 " " " " " 1 day.
D. " 600° C. " 1 " " " " " 70 days.
E. " 800° C. " 1 " " " " " 13 "
F. " 800° C. " 1 " " " " " 70 "
G. " 800° C. " 1 " " " " " 147 "
H. " 800° C. " 1 " " " " " 275 "

FIG. 4. Differential thermal curve of illite, Grundy County, Illinois.

A. Not heated.
B. Heated 450° C. for 1 hour, curve run after standing 7 days.
C. " 450° C. " 1 " " " " " 55 "
D. " 550° C. " 1 " " " " " 4 "

(Legend continued on page 54)

The curves show that after heating to 600°C. (curves B–D) some pickup of adsorbed water and (OH) lattice water is very rapid. Apparently a considerable portion of both kinds of water is taken up quickly and further amounts are taken up at a slow gradual rate. The curves show also that loss of the rehydrated (OH) water begins at a lower temperature (400°C.) than that of the original (OH) water (475°C.).

On standing after heating to 800°C. (curves E–H) there is a gradual regaining of adsorbed water and (OH) lattice water. The similarities of the curves for 147- and 275-day standing periods suggest that after a certain amount of rehydration takes place, any further pickup of water is slight and very slow.

The final part of the curve, showing reactions corresponding to destruction of lattice and the formation of a new phase, is unchanged by the dehydration and rehydration.

The curves for the illite purified from the Grundy County, Illinois, clay presented in Fig. 4 shows that this sample has the same general rehydration properties as those of the previously considered illite. The rehydration of the Grundy County illite appears to be slower and without any suggestion of a lowering of the temperature required to remove the water gained on rehydration.

The rehydration characteristics of an illite from the Minford silt of Ohio are shown in Fig. 5. The adsorbed water is picked up slowly and gradually on material heated to 600°C. so that after 217 days (curve L) there appears to be more adsorbed water than there was in the original sample. Adsorbed water is picked up also after heating to 800°C. (curve M).

The curves show a slight regaining of (OH) lattice water after heating to temperatures as high as 800°C. The amount of (OH) water regained is small—considerably smaller than the previously considered illites. There is no indication that the samples heated to 500°C. (curves B, C) regained more water on rehydration than the sample heated to 800°C. (curve M).

E.	“	550° C.	“	1	“	“	“	“	“	17	“
F.	“	550° C.	“	1	“	“	“	“	“	55	“
G.	“	550° C.	“	1	“	“	“	“	“	221	“
H.	“	600° C.	“	1	“	“	“	“	“	1	“
I.	“	600° C.	“	1	“	“	“	“	“	9	“
J.	“	600° C.	“	1	“	“	“	“	“	17	“
K.	“	600° C.	“	1	“	“	“	“	“	53	“
L.	“	600° C.	“	1	“	“	“	“	“	223	“
M.	“	800° C.	“	1	“	“	“	“	“	12	“
N.	“	800° C.	“	1	“	“	“	“	“	70	“
O.	“	800° C.	“	1	“	“	“	“	“	146	“
P.	“	800° C.	“	1	“	“	“	“	“	278	“

In some of the Minford silt samples, illite occurs associated with a chlorite. Although no chlorite was apparent by x-ray diffraction or optical examination of the sample used in this study, it is not unlikely that the variations of these curves from those of the other illites are nevertheless due to the admixture of undetected chlorite.

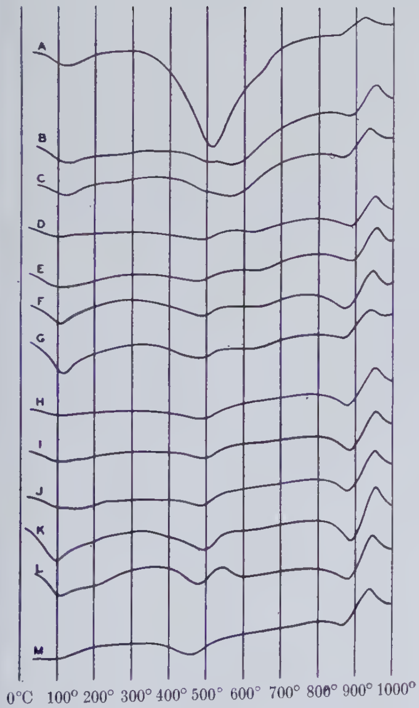


FIG. 5

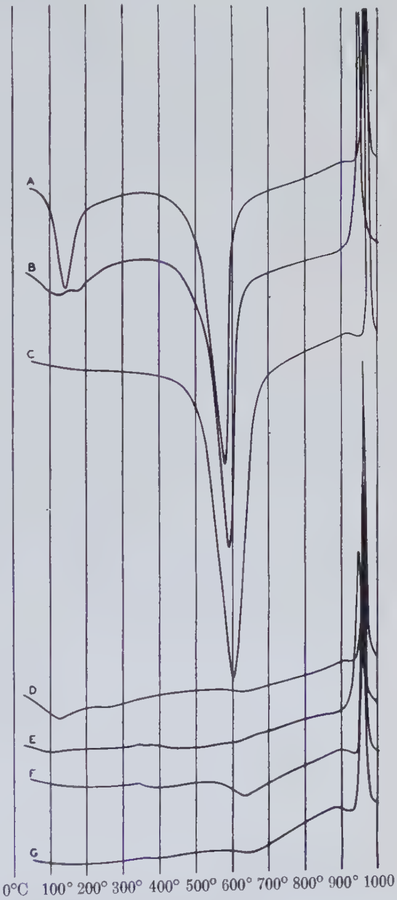


FIG. 6

FIG. 5. Differential thermal curves of illite from Minford silt, Ohio.

A. Not heated.
B. Heated 500° C. for 1 hour, curve run after standing 14 days.
C. " 500° C. " 1 " " " " " 163 "
D. " 550° C. " 1 " " " " " 2 "
E. " 550° C. " 1 " " " " " 16 "
F. " 550° C. " 1 " " " " " 52 "
G. " 550° C. " 1 " " " " " 218 "

(Legend continned on page 56)

Halloysite and kaolinite

The kaolinite represented by curve B in Fig. 6 is rather poorly crystallized, whereas that represented by curve C is very well crystallized (4). The curves for these two kaolinites show pronounced differences (*a*) in the intensity of the reactions, (*b*) in the presence of an initial endothermic reaction in the poorly crystallized kaolinite, and (*c*) in the presence of a slight endothermic reaction at about 930°C. in the well crystallized sample.

The thermal curve D in Fig. 6 shows that after heating to 600°C. there is a very slight pickup of adsorbed water by the halloysite sample, but in the light of the known highly porous condition of halloysite aggregates, it is probable that this represents merely adsorbed rather than crystalline water. There is also a suggestion of the regaining of a trace of (OH) lattice water.

Curve E for the poorly crystallized kaolinite suggests the pickup of a trace of adsorbed water, but there is no positive indication of the regaining of any (OH) water.

The well crystallized kaolinite (curves F and G) shows a distinct pickup of a very small amount of (OH) lattice water after heating to 600°C.

The final part of the curves are substantially unchanged by heating to 600°C. It is significant that the halloysite and well crystallized kaolinite which show an endothermic reaction at about 920–930°C. show some regaining of (OH) lattice water, whereas the poorly crystallized kaolinite which shows no final endothermic reaction also shows no regaining of (OH) lattice water.

H.	"	600° C.	"	1	"	"	"	"	"	2	"
I.	"	600° C.	"	1	"	"	"	"	"	7	"
J.	"	600° C.	"	1	"	"	"	"	"	16	"
K.	"	600° C.	"	1	"	"	"	"	"	52	"
L.	"	600° C.	"	1	"	"	"	"	"	217	"
M.	"	800° C.	"	1	"	"	"	"	"	6	"

FIG. 6. Differential thermal curves of kaolinites and halloysite.
- A. Halloysite (partially hydrated form), Eureka, Utah. Not heated.
- B. Kaolinite, Anna, Illinois, not heated.
- C. Kaolinite, Dry Branch, Georgia, not heated.
- D. Halloysite heated 600° C. for 1 hour, curve run after standing 70 days.
- E. Kaolinite, Anna, Illinois, heated 600° C. for 1 hour, curve run after standing 70 days.
- F. Kaolinite, Dry Branch, Ga., heated 600° C. for 1 hour, curve run after standing 70 days.
- G. Kaolinite, Dry Branch, Ga., heated 600° C. for 3 hours, curve run after standing 7 days.

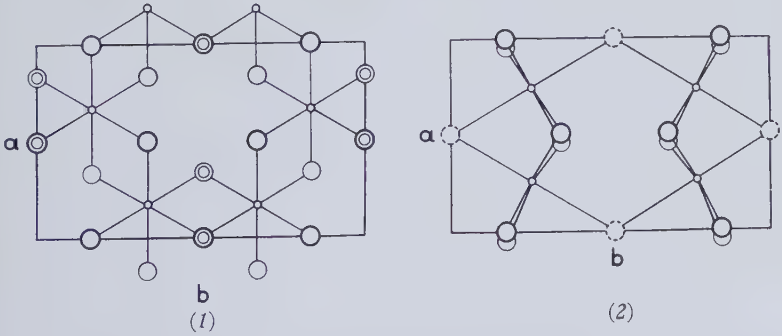
Discussion of Results

Quite a surprising number of common minerals, not otherwise so obviously related, are based upon variations of a single characteristic assemblage of oxygen and hydroxyl ions coordinated about various combinations of particular cations. This structural unit, with the proportion of 20 oxygen ions to 4 hydroxyl ions, is encountered in the crystallizations of the micas, talc, pyrophyllite, the chlorites, the montmorillonite group minerals, the illites and probably several others.

For the better crystallized examples of this structural type the hydroxyl water is not very readily removed by firing, and any approach to equilibrium conditions at a given temperature is so slow that they do not lend themselves to thermal analysis. For the two fine-grained groups, however, the illites and the montmorillonites, the thermal expulsion of this water has become a well-known diagnostic feature in numerous thermal analysis studies, and it has been generally noted that the illites lose this water at about 100–150°C. lower temperature than do the montmorillonites.

It has been remarked before (5, 6) that this type of fundamental structural unit is able to survive the abstraction of its hydroxyl water with only moderate readjustment, but detailed analysis has not been attempted.

In connection with a related study of heat effects (6), occasion has arisen to examine several montmorillonites after ignition to temperatures just above those necessary to remove the hydroxyl water. *X*-ray diffraction diagrams obtained from such material are found to be consistent with effects to be anticipated from the relatively simple layer rearrangement illustrated in Fig. 7. The two packed layers of octahedrally co-



(*1*) (*2*)

FIG. 7. Schematic representation of the configurations in the layers of octahedral coordination (*1*) before and (*2*) after condensation of the (OH) lattice water of the three-layer silicates. Large circles represent oxygen, double circles hydroxyl, and small circles aluminum or magnesium.

ordinated ions are merely shifted from the packed position to one of direct apposition, with each pair of hydroxyl ions being replaced by a single residual oxygen ion set between two hydroxyl positions.

It is noted that the described arrangement affords a reasonably adequate disposition for four octahedrally coordinated cations per unit cell per layer as in a heptaphyllite type, but would demand a highly unreasonable sequence of shared coordination octahedron faces for an octaphyllite type mineral. Neither the 500°–700°C. endothermic peak nor the characteristically modified diffraction diagram is observed for the one certain example of octaphyllite clay (the "hectorite") which was available in the study referred to above.

The quantity of hydroxyl water taken into recombination by these montmorillonites amounts to only about one-fourth the original hydroxyl water and does not afford any clear cut x-ray diffraction inference, but in the light of the anhydrous configuration illustrated, it seems reasonable to assume that only a small part is recombined into the original configuration, with an additional significant amount attaining only some other bonding of lower energy.

The nature of the micas is such that they do not afford even the limited data that are obtainable from the montmorillonites. The pairing of layers in the muscovite structure, which is presumably also present in illites, reduces the natural β angle so nearly to 90° that such a shift as the one described for montmorillonites results in too slight an effective shift for the double layer to be clearly observable in the diffraction diagrams. For this same reason, however, we can feel that the more intimate association of adjacent layers not only permits easier abstraction of the interior hydroxyl water, as evidenced by the lower temperature of the endothermic reaction, but also promotes the reversibility of the recombination and reabstraction of such water.

The structural unit upon which the crystallization of the kaolinite minerals is based is less stable and does not survive the loss of its (OH) water as a conventional crystal. Some degree of order does persist however, the state being commonly designated as "metakaolin." The thermal curves for the two-layer clay minerals indicate that a noticeable amount of (OH) lattice water rehydration takes place for the halloysite and the well crystallized kaolinite, but that none takes place in the poorly crystallized kaolinite. It is significant that the samples showing rehydration also show the small endothermic reaction at about 930°C. Although not well shown by the curves presented herein, differential thermal analyses of a very large number of kaolinites have shown that when the endothermic peak at about 930°C. is present, there is also a definite upward slope to the curve between the endothermic peak at about 600°C. and the 930°C. peak, and that when the 930°C. endothermic reaction is not present the curve is horizontal between the 600°C. endothermic peak and the final exothermic reaction. The best interpretation of the foregoing observations seems to be that in the case of at least some halloysites and in well crystallized kaolinites, the structural remnant which makes up the "metakaolin" retains sufficient regularity to recombine at least minor amounts of (OH) water, and that some of this structure persists even up to about 930°C.

References

1. Grim, R. E., and Rowland, R. A., Differential thermal analyses of clay minerals and other hydrous materials: *Am. Mineral.* **27,** 746–761, 801–818 (1942); *Ill. Geol. Surv., Rept. Inv.* **85** (1942).
2. Grim, R. E., and Bradley, W. F., Investigation of the effect of heat on the clay minerals illite and montmorillonite: *Jour. Am. Cer. Soc.*, **23,** 242–248 (1940); *Ill. Geol. Surv., Rept. Inv.* **66** (1940).
3. Grim, R. E., Bray, R. H., and Bradley, W. F., The mica in argillaceous sediments: *Am. Mineral.* **22,** 813–829 (1937); *Ill. Geol. Surv., Rept. Inv.* **44** (1937)
4. Grim, R. E., Differential thermal curves of prepared mixtures of clay minerals: *Am. Mineral.*, **32,** 493–501 (1947)
5. Thilo, E., and Schünemann, H., The behavior of pyrophyllite, $Al_2(Si_4O_{10})(OH)_2$, on heating and the existence of an anhydrous pyrophyllite $Al_2(Si_4O_{10})$-O: *Zeit. anorg. Allgem. Chem.*, **230,** 321–335 (1937).
6. Grim, R. E., and Bradley, W. F., High temperature thermal effects of clays and related materials: Presented at the Annual Meeting of the Mineralogical Society of America, December 1945.

RELATIONS AMONG CRYSTALLOGRAPHIC ELEMENTS

HOWARD T. EVANS, JR.,
Section of Graphics, Massachusetts Institute of Technology.

ABSTRACT

Explicit formulae are given relating the three sets of morphological elements for the triclinic system: axial, projection and polar elements.

It has become customary, when reporting morphological data in the literature, to record the values of certain characteristic constants or elements. For a triclinic crystal, the most general case, there are five, and these are customarily computed in three different ways. This process yields the axial elements (a, c, α, β, and γ), the projection elements (x_0', y_0', p_0', q_0', and ν), and the polar elements (p_0, q_0, λ, μ, and ν). While all these values are given in modern references (such as the 7th edition of *Dana's System of Mineralogy*), the larger proportion of data in the literature provides only the axial elements, especially with respect to artificial compounds. Naturally, each element is explicitly expressible in terms of the elements of any other set; such expressions would enable the crystallographer to transform from one set to another at his convenience. These relationships have been derived and found very useful in this laboratory. Since they do not appear to be published together anywhere, at least within easy reach, it seems worthwhile to record them here.

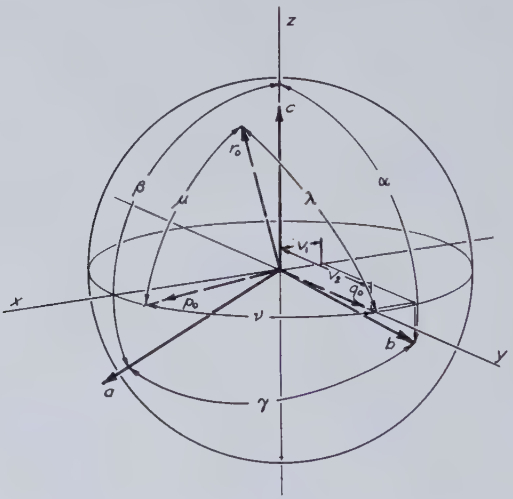


FIG. 1. Triclinic axes and angles.

The elements listed above are described by means of two sketches, Fig. 1 and Fig. 2. For further definitions and relations, see the Introduc-

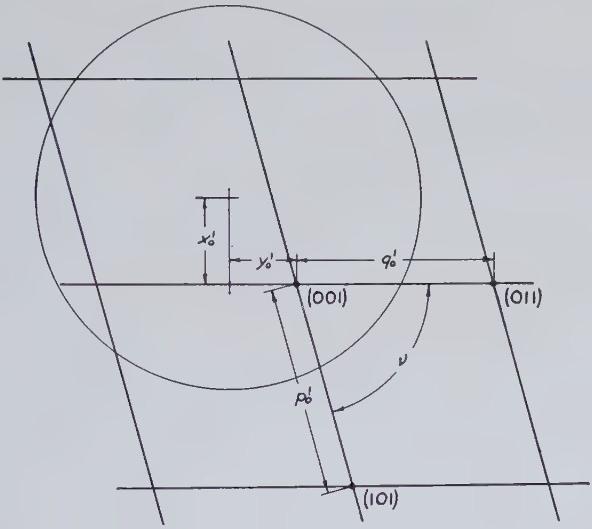


FIG. 2. Triclinic gnomonic projection.

tion to the *System*.[1] Two additional constants are of great value in these formulae. These are the components v_1 and v_2 of the unit *b*-axis on the *x*- and *y*-axes of Cartesian coordinates, respectively. The most useful transformation formulae are collected in Table 1.

TABLE 1. TRANSFORMATION FORMULAE AMONG THE THREE SETS OF TRICLINIC ELEMENTS

$$v_1 = \frac{\cos\gamma - \cos\alpha\cos\beta}{\sin\beta} \tag{1}$$

$$v_2 = \frac{\sqrt{1 + 2\cos\alpha\cos\beta\cos\gamma - (\cos^2\alpha + \cos^2\beta + \cos^2\gamma)}}{\sin\beta} \tag{2}$$

$$v_1 = -\frac{\cos\nu}{\sqrt{1 + (x_0'\cos\nu - y_0'\sin\nu)^2}} \tag{3}$$

$$v_2 = \frac{\sin\nu}{\sqrt{1 + (x_0'\cos\nu - {}_0'\sin\nu)^2}}\,. \tag{4}$$

Axial elements:

$$a = \frac{q_0' v_2 \sqrt{1 + x_0'^2}}{p_0'\sin\nu} \tag{5}$$

$$c = q_0' v_2 \tag{6}$$

$$\cot\alpha = x_0'\cos\nu - y_0'\sin\nu \text{ [2]} \tag{7}$$

$$\cot\beta = -x_0' \tag{8}$$

$$\cos\gamma = \frac{v_1 + x_0'(v_1 x_0' + v_2 y_0')}{\sqrt{1 + x_0'^2}} \tag{9}$$

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[1] Palache, Berman and Frondel, *Dana's System of Mineralogy*, 7th ed., pp. 3–37; John Wiley & Sons, Inc., New York (**1944**). This section is reprinted from C. W. Wolfe, *Am. Mineral.*, **26**, 55–91 (1941).

[2] The relation: $\sin\alpha = \sqrt{v_1^2 + v_2^2}$, is also useful, but is not used in this list because of the ambiguity with regard to the quadrant of α.

Table 1—(*continued*)

Projection elements:

$$x_0' = -\cot \tag{10}$$

$$y_0' = \frac{v_1 \cot \beta - \cos \alpha}{v_2} \tag{11}$$

$$p_0' = \frac{c \sin \alpha}{a v_2 \sin \beta} \tag{12}$$

$$q_0' = \frac{c}{v_2} \tag{13}$$

$$\tan \nu = -\frac{v_2}{v_1} \tag{14}$$

Polar elements:

$$r_0' = \sqrt{x_0'^2 + y_0'^2 + 1} \tag{15}$$

$$p_0 = \frac{p_0'}{r_0'} \tag{16}$$

$$q_0 = \frac{q_0'}{r_0'} \tag{17}$$

$$\cos \lambda = \frac{y_0'}{r_0'} = y_0 \tag{18}$$

$$\cos \mu = \frac{x_0' v_2 - y_0' v_1}{r_0' \sqrt{v_1^2 + v_2^2}} \tag{19}$$

$$\tan \nu = -\frac{v_2}{v_1}. \tag{20}$$

By appropriate substition of $\alpha = \gamma = 90°$, these formulae may be rewritten for the monoclinic system. Thus, $v_2 = 1$ and v_1 vanishes. The results are so greatly simplified that they may be written down at once by inspection of Table 1. The remaining systems become trivial.

The constants v_1 and v_2 are seen to be very useful in the expression of these formulae. They are so much so in all calculations in this system that the first step in any study of a triclinic crystal, once a particular orientation is chosen, should be their evaluation. It is therefore urged that v_1 and v_2 be included in the description of a triclinic crystal, even at the risk of increasing the bulk of data already recorded for this system.

Very briefly, the best approach to these formulae is described as follows. W. L. Bond[3] has expressed the components of the triclinic axes on the axes of Cartesian coordinates in terms of a matrix:

$$M = \begin{Vmatrix} a \sin \beta & v_1 & 0 \\ 0 & v_2 & 0 \\ a \cos \beta & \cos \alpha & c \end{Vmatrix}$$

[3] Bond, W. L., *Am. Mineral.*, **31**, 31–42 (1946).

The columns contain the x, y, and z components of the a, b, and c axes respectively, v_1 and v_2 are the constants already given by equations 1–4 of Table 1. The transposed reciprocal of this matrix is also given by Bond:

$$\overline{M}^{-1} = \left\| \begin{array}{ccc} \dfrac{1}{a \sin\beta} & 0 & -\dfrac{\cot\beta}{c} \\ -\dfrac{v_1}{a v_2 \sin\beta} & \dfrac{1}{v_2} & \dfrac{v_1 \cot\beta - \cos\alpha}{v_2 c} \\ 0 & 0 & \dfrac{1}{c} \end{array} \right\|$$

Here the columns contain the Cartesian components of the axes of the reciprocal cell. The reciprocal axes have the ratio $p_0:q_0:r_0(=1)$ and are separated by the interaxial angles λ, μ and ν. By matrix multiplication of the reciprocal vectors (face normals) (001), (101), and (011) with $\overline{M}^{-1}$, their respective Cartesian components are obtained. If these vectors are extended to the gnomonic projection plane ($z=1$), these components are then simple functions of the projection elements. The polar elements are then simply scaled down from the projection elements by the length of the (001) vector (r_0').

SUMMARY

Relationships have been derived among the three sets of triclinic elements, axial, projection and polar elements. These are given in a table as a list of formulae. They are derived by a study of vectors in the reciprocal cell and their components on Cartesian axes. It is hoped that they will be of use in triclinic calculations in general; for example: (1) to derive projection elements from references where only axial elements are given, for the purpose of making graphical measurements and crystal drawings; (2) to derive axial elements from projection elements obtained from newly measured crystals, as a check against published data, or for the preparation of new data; (3) to derive polar elements as a check against x-ray data.

FLUORITE-RARE EARTH MINERAL PEGMATITES OF CHAFFEE AND FREMONT COUNTIES, COLORADO*

E. Wm. Heinrich, *University of Michigan, Ann Arbor, Michigan.*

Abstract

A small group of pegmatites in Chaffee and Fremont Counties, Colorado, is characterized by the association of fluorite with the rare earth minerals, euxenite, monazite, allanite, and gadolinite. The deposits, which are differentiated into central and outer zones of contrasting texture, formed chiefly during the magmatic stage. The less common minerals are the result of hydrothermal modification. Fluorite and rare earth minerals are associated in 19 of the 22 pegmatite districts in North America from which fluorite has been reported. This geochemical relationship is emphasized by the widespread occurrence of rare earth elements in fluorites.

Introduction

The purpose of this paper is to describe a small group of fluorite and rare earth mineral pegmatites in Chaffee and Fremont Counties, Colorado, and to compare the group with other pegmatite districts.

The writer examined the deposits during the summer of 1946 while engaged in field work in south-central Colorado. A part of the field expenses was met by a generous grant from the Brodrick fund of Harvard University. Mr. J. E. Meyers of Canon City, Colorado, acted as guide for the writer and deserves special thanks for his generous assistance.

The pegmatite bodies are in southwestern Fremont County and in northeastern Chaffee County, Colorado. The location of the four deposits described in detail, as well as a number of other pegmatites to which reference is made, is shown in Fig. 1. Although the Yard pegmatite locality has been known to mineral collectors for a number of years, the writer could find no description of any of the deposits in the literature.

The pegmatite areas are underlain by pre-Cambrian metamorphic and igneous rocks. The metamorphic formations are chiefly mica schist, mica gneiss, and local quartzite and hornblende gneiss. The fluorite-rare earth mineral pegmatites appear to be confined to pre-Cambrian granite that may possibly be correlated with the Pikes Peak granite of the Colorado Front Range. The physical resemblance is close but no age determinations have been made.

The pegmatites are found in two areas separated by a large down-faulted block of Carboniferous sediments that forms the northern end of the Sangre De Cristo Range. The Trout Creek Pass area is north and west of the end of the range and centers around Trout Creek Pass east of

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* Contribution from the Department of Mineralogy and Petrography, Harvard University, No. 293.

Buena Vista (Fig. 1). The Cotopaxi area lies north of Cotopaxi along the east side of Barnard Creek (Fig. 1).

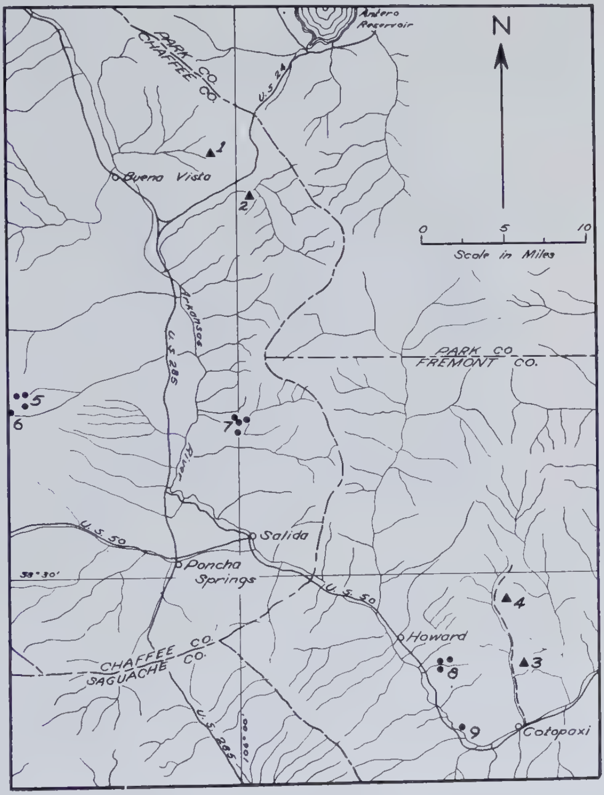

FIG. 1. Index map showing location of fluorite-rare earth mineral pegmatites in Chaffee and Fremont Counties, Colorado (marked by triangles): 1. Yard pegmatite, 2. Luella pegmatite, 3. Colorado feldspar pegmatite, 4. Pine Ridge pegmatite. The locations of other pegmatite deposits mentioned are shown by circles: 5. Mt. Antero group, 6. Browns Canyon molybdenite pegmatite, 7. Turret group, 8. Howard group, 9. Coaldale pegmatite.

YARD PEGMATITE

The Yard pegmatite is in the southwestern part of T. 15 S., R. 77 W. and lies about 1½ airline miles N. 50° E. of the junction of U. S. highways 284 and 24, which is south of Buena Vista. The deposit is claimed by Ernest Yard of Canon City, Colorado, who worked it in the early 1940's chiefly for feldspar. Many museum specimens of euxenite and monazite also have been obtained.

The main workings, which are about 150 feet above a gulch on the southwest slope of a 250-foot hill, consist of an open cut, 100 feet long, 40 feet in maximum width, and 35 feet deep at the face. Two levels have been made. Two trenches serve as entryways and a small narrow cut branches from one side. Near the top of the hill is a narrow, north-trending trench, 15 feet long, also in pegmatite.

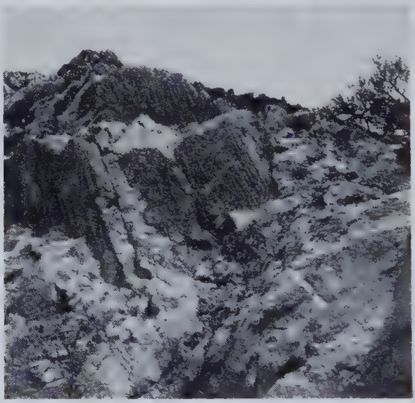

FIG. 2. Photograph of biotite sheets along fractures in core of Yard pegmatite, Chaffee County, Colorado.

The pegmatite strikes N. 60° E. and dips 60° N.W. In the open cut it is about 70 feet wide, but it narrows toward the crest of hill to 40 feet. It can be traced down the northeast slope for only a short distance; thus the keel of the body may plunge at a steep angle to the west-southwest. The pegmatite is also exposed below the dumps from the main cut and can be followed into the gulch where it is only 15 feet thick. A three-foot thickness crops out across the gentle slope of the southwest side of the gully for 200 feet, at which point the body ends in a pod of white quartz. The total length of the exposure is about 600 feet.

The country rock is a light-colored, medium-grained granite with subordinate porphyritic and coarse-grained phases. Locally with a decrease in the amount of biotite and a diminution of the general grain size the rock becomes aplitic. The hanging-wall pegmatite contact is sharp, but the footwall contact is poorly defined and the two rocks intergrade in some places.

In the thickest part of the deposit, i.e., in the open cut, the pegmatite is differentiated into a central zone or core and a surrounding wall zone. The core consists of pods of milky quartz, 6 feet or less in length, and masses of coarsely crystalline microcline as much as 15 feet long. Many of the microcline crystals have been partly removed in mining. The wall zone, which is poorly exposed in the main cut, consists of graphic granite, quartz, microcline, and uncommon, one-inch magnetite crystals in a medium-grained intergrowth. In the gully a 4-foot core of quartz is surrounded by a similar wall-zone rock.

Along the margins of the core are local concentrations of fluorite and rare earth minerals associated with tabular bodies of muscovite. Much of the central part of the core has been strongly fractured. Of the several sets of fractures, one of the most prominent strikes N. 50° W. Sheets of biotite as much as 3 feet long, 2 feet wide, and 1 foot thick have formed along many of the cracks (Fig. 2). Similar blades of biotite, some of them 6 feet long, occur in the upper trench, cutting wall-zone pegmatite rich in graphic granite.

The primary minerals of the core and the wall zone are quartz, microcline, and magnetite. The other minerals are later and form fracture fillings or replacement masses many of which are clearly related to fractures.

The wall-zone pegmatite has been altered by small, patchy replacements and narrow veins in which green muscovite and light colored albite are abundant. Local vugs, four inches deep, which have been formed by solution of microcline, contain small muscovite and quartz crystals, $\frac{1}{4}$ inch long. Some of the muscovite plates have been replaced by bright yellow sericite. Veinlets of purple fluorite, quartz, chlorite, and specular hematite also are present. Much of the wall-zone microcline, which normally is either white or pale pink, has been changed to green by incipient sericitization. Albite, one of the early replacing minerals, is replaced by later chlorite.

The sequence of veining and replacement in the wall zone appears to be:

1. Muscovite and albite
2. Purple fluorite, quartz, and chlorite
3. Specular hematite
4. Sericite

Around the margins of the core occur local concentrations of monazite, euxenite, fluorite, and plagioclase, usually in the form of one-inch to one-foot pods and clusters of crystals. These masses appear to have formed by replacement of core rock and commonly are localized along a contact between a quartz pod and a microcline crystal. Associated with these masses are tabular veins of muscovite, five feet or less in length. The mica is grayish green in color and occurs in six-inch wedge-shaped blades, marked by ruling and A-structure.

Pods of monazite and the closely associated euxenite are surrounded by aureoles of pink to dark red feldspar, a regular feature accompanying the occurrence of these minerals. Series of cracks radiating from a central euxenite aggregate also are conspicuous. Monazite was found in masses as large as 4.5×2.5×2 inches (Fig. 3), and the largest piece of euxenite obtained measures 2.5×2×1.5 inches (Fig. 4). The monazite is cut by

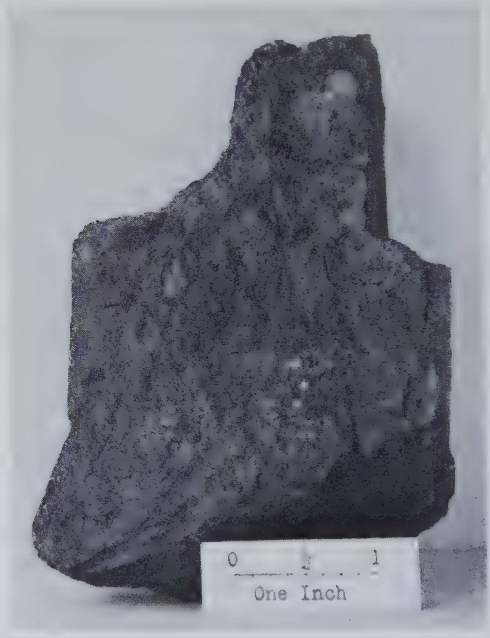

Fig. 3. Photograph of largest monazite fragment found in Yard pegmatite. The shiny spangles are specular hematite.

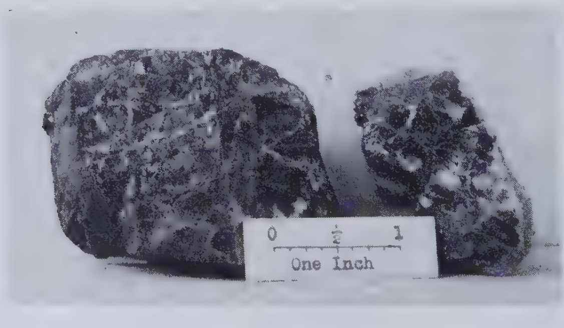

Fig. 4. Euxenite from Yard pegmatite showing fractures filled with typical greenish alteration product.

fractures, some of which are coated by specular hematite (Fig. 3). The euxenite pods are minutely fractured and break easily into many small pieces. Along the fracture surfaces are films of an earthy, buff to greenish material (Fig. 4), a common alteration product of this mineral (Palache et al. 1944, p. 791). A single cluster of three sub-parallel crystals was found, the largest of which is $\frac{5}{8}$ inch long, $\frac{3}{8}$ inch across, and $\frac{1}{8}$ inch thick. The forms present are: *a*{100}, *b*{010}, and *d*{101}.

Both monazite and euxenite replace and vein the white plagioclase (calcic albite to sodic oligoclase) and are themselves veined and corroded by white fluorite, red albite, and an unidentified soft yellow-gray mineral. The monazite, which appears to be slightly older than the euxenite, is associated with a few small blebs of gadolinite and is cut by minute veinlets of apatite as well as specular hematite.

About 300 pounds of white to buff fluorite has been stockpiled near the mouth of the main cut, but only small amounts of this mineral were observed in place. Lumps 8 inches across are not uncommon. Rare, minute veinlets of purple fluorite transect the white variety.

Bismutite is reported to be abundant locally in the deposit. A three-inch piece, presented to the writer by J. B. Leslie of Canon City, Colorado, occurs in quartz and is gray, brown, and green in color. No relicts of the original mineral remain. Malachite stains part of the specimen. According to Mr. Leslie 800 pounds of bismutite has been obtained from this pegmatite.

The sequence of formation of the minerals in the replacement pods appears to be as follows:

1. White albite-oligoclase, muscovite
2. Monazite and gadolinite
3. Euxenite
4. White fluorite and red albite
5. Unidentified, soft, gray mineral
6. Purple fluorite, apatite
7. Specular hematite
8. Sericite
9. Bismutite and malachite

LUELLA PEGMATITE

The Luella pegmatite is 3 miles S. 40° E. of the Yard deposit and just southeast of U. S. highway 24 (Fig. 1). The deposit was claimed on May 1, 1946, by Messrs. C. J. Vesey, C. Miles Martin, and E. Moldenhauer of Denver, Colorado, and it has been worked in the past by Magnusson and Sons of Denver for feldspar. The open cut, which is 60 feet long and 20 feet wide, has two levels: the floor, 30 feet below the rim, and an eastern bench 13 feet higher.

The pegmatite body strikes N. 67° E. and dips 68° SE. In the cut it is at least 50 feet thick, but 150 feet to the east it thins to 5 feet. The total exposed length is about 250 feet. The footwall contact is not exposed. The hanging-wall contact with the country rock, a coarse-grained porphyritic granite, is generally sharp, except in the entryway to the cut, where a gradational rock is exposed.

The well-developed zonal structure includes:

1. A one- to two-inch border zone of fine-grained pink microcline and quartz.
2. A wall zone, five to eight feet thick, consisting of pink microcline masses, one and one-half feet on edge or less, set in a medium-grained matrix of anhedral quartz and pink microcline.
3. A core, 30 feet thick, containing chiefly very coarse blocky microcline in its central part, surrounded by a poorly defined periphery of quartz pods. The open cut has been made in the central microcline-rich part of the core. Rose quartz occurs in the core near its western end.

A three-foot inclusion of slightly pegmatitized granite appears in the cut floor. On the footwall side of the core near the southwest corner of the cut is exposed a pod of brick-red plagioclase-rich rock, three by two feet in section. Here the wall zone contains small vugs and abundant fractures, some of which are lined with biotite strips as much as one foot long and three inches thick. Other cracks are coated by flattened ½-inch garnet crystals. Minerals occurring within the plagioclase unit are muscovite, allanite, euxenite, apatite, hematite, garnet, fluorite, and bismutite.

The primary minerals are quartz and microcline. All the other constituents occur in or around a replacement unit localized in wall zone rock near the footwall contact with the core. The chief feldspar of the pod is red plagioclase (albite to sodic oligoclase), but a few relicts of pink microcline remain. Allanite, which is next in abundance (about 10%), occurs as striated prismatic crystals, as much as an inch thick and several inches long. A single minute crystal of apatite was found along the side of one of the allanite blades. Euxenite is relatively rare; only a few ½-inch fragments were obtained. Green fluorite veins and replaces microcline, and a few small veinlets of purple fluorite transect plagioclase. During later stages of the hydrothermal activity, solution exceeded deposition, and small vugs formed at the expense of plagioclase, allanite, and green fluorite. Extensive sericitization accompanied the production of the cavities. Late to form were bismutite and supergene calcite and limonite.

The sequence of formation of the secondary minerals appears to be:

1. Plagioclase and minor muscovite
2. Biotite and garnet
3. Allanite, euxenite, apatite
4. Green fluorite, purple fluorite
5. Hematite

6. Sericite and vugs
7. Bismutite
8. Calcite and limonite

COLORADO FELDSPAR PEGMATITE

The Colorado Feldspar pegmatite is in sec. 8, T. 48 N., R. 12 E., and lies four miles N. 5° E. of Cotopaxi. The deposit was quarried in 1939 by the Colorado Feldspar Company of Canon City, who recovered several hundred tons of potash feldspar. The pegmatite has been mined from an open cut 60 feet long, 40 feet wide, and 8 feet deep at the face.

Except in the cut, exposures are poor, and part of the pegmatite may be covered by dump material. No contacts are exposed, but from the general configuration of the exposures the body may be flat-lying and irregular in outline. Zoning is poorly developed, and most of a poorly-defined 10-foot core of white microcline and massive milky quartz has been removed in mining. A few 2-foot feldspar crystals are still exposed in the cut walls. The outer zone consists of irregular masses of graphic granite and granitic quartz-microcline rock containing a few distorted octahedrons of magnetite, one inch on edge. Much of this material has been attacked by later solutions and replaced by later minerals, including plagioclase, biotite, hematite, fluorite, euxenite, monazite, sericite, and calcite.

Near the pegmatite exposures the country rock is a strongly gneissic biotite granite, but in the gully to the south typical Pikes Peak granite is exposed, distinguished by the aligned phenocrysts of red microcline in a coarse-grained matrix. About ¼ mile south of the cut in the same drainage several small magnetite-bearing pegmatites crop out. A few pieces of euxenite were obtained from one body.

The wall zone rock has been replaced in an irregular, patchy pattern by secondary material, the bulk of which is white plagioclase (albite to sodic oligoclase) and biotite. Biotite is especially abundant locally, occurring in aggregates of blades some of which are a foot long and three to six inches thick. Most of it has been altered to chlorite. White fluorite in three-inch pods also replaces microcline and is in turn veined by purple fluorite.

Euxenite and monazite appear to have formed next. The former occurs in two ways: as ½-inch rounded masses, but much more commonly as thin radiating blades, two inches long. Much of the euxenite shows alteration, three stages of which can be recognized: the zone nearest the fresh mineral (and presumably the first stage in the decomposition) is a light brown material with a pitchy luster; the inner zone consists of a substance with a similar luster but yellow in color; and the outer part is made up of a bright yellow, earthy, and friable material. Monazite was found in several four-inch hemispherical masses of radiating crystals. The individual blades are 1½ inches long and as much as ¾ inch thick at the convex surface, where they are terminated by imperfect crystal faces. Both minerals were found in relative abundance in the eastern part of the deposit. One mass of euxenite weighed 75 pounds.

Following the formation of vugs, chiefly by the dissolution of fluorite, specular hematite and pink calcite were deposited in the openings. The former also occurs in small, sharply defined veinlets cutting quartz and feldspar. This stage was also marked by the formation of sericite. With incipient sericitization microcline was changed in color from cream to pale green.

Pine Ridge Pegmatite

The Pine Ridge pegmatite lies nearly 7 miles N. 4° W. of Cotopaxi in sec. 20, T. 49 N., R. 12 E. The deposit was discovered in late 1941 by Mr. Frank Ogden of Vallie, Colorado, who prospected it for feldspar by digging a narrow, shallow trench about 10 feet long.

The poorly exposed, narrow pegmatite appears to strike north-south. No contacts were observed. The cut exposes a central unit of brick-red microcline, massive white quartz, and abundant biotite. Gadolinite, associated with white plagioclase, gray fluorite, and green sericite, occurs as a replacement of microcline.

As in the other pegmatites described, quartz and microcline are primary. Biotite occurs in blades cutting across the fabric of the quartz-feldspar intergrowth. White sodic oligoclase and rare fluorite cross microcline and appear to be contemporaneous with gadolinite. The rare earth mineral is black with a resinous luster and occurs in masses as large as 20 pounds. The last mineral to form was green sericite.

Other Pegmatites in the Region

Figure 1 shows the location of other pegmatites in the region. In Group 5 are the Mount Antero-White Mountain pegmatites which have been described most recently by Switzer (1939). These deposits are marked by a hydrothermal beryllium-fluorine phase and are believed to be Tertiary in age. No. 6 is the Browns Canyon quartz-molybdenite pegmatite described by Landes (1934). Pegmatites near Turrett (Group 7) contain late-stage albite, muscovite, garnet, and beryl. Those southeast of Howard (Group 8) are characterized by secondary albite, biotite, muscovite, and garnet. Primary magnetite is exceedingly abundant locally. In the Coaldale pegmatite (No. 9) primary hornblende and hydrothermal epidote were noted.

ASSOCIATION OF FLUORITE AND RARE EARTH MINERALS

Fluorite and other fluorides have been reported in pegmatites of five districts in Colorado and in 17 other districts in North America. In 19 of these fluorite is associated with rare earth minerals. This relationship is summarized in Table 1.

TABLE 1. FLUORITE PEGMATITES OF NORTH AMERICA

District	Host Rocks	Fluorine Minerals	Rare Earth Minerals	Reference
1. Trout Creek Pass-Cotopaxi District, Chaffee and Fremont Counties, Colo.	(a) pre-Cambrian pegmatites	fluorite	monazite, allanite, euxenite, gadolinite	Heinrich
	(b) Tertiary pegmatites	fluorite, topaz	—	Switzer (1939)
	(c) Tertiary veins	fluorite	—	Cox (1945)
2. Quartz Creek District, Gunnison County, Colo.	pre-Cambrian pegmatites	fluorite, topaz	monazite, euxenite(?)	Heinrich (1942) Hanley (1946)
3. Jamestown District, Boulder County, Colo.	(a) pre-Cambrian pegmatites	fluorite, bastnäsite, törnebohmite	cerite, allanite, törnebohmite, bastnäsite, monazite (uraninite)	Goddard and Glass (1940)
	(b) Tertiary veins	fluorite		Cox (1945)
	(c) Tertiary bostonite	fluorite as accessory mineral	—	Cox (1945)
4. Pikes Peak District, El Paso and Teller Counties, Colo.	(a) pre-Cambrian pegmatites	fluorite, pachnolite, prosopite, gearksutite, cryolite, thomsenolite, ralstonite, fluocerite, bastnäsite, elpasolite, topaz	bastnäsite, fluocerite, fergusonite	Cross and Hillebrand (1885), Over (1929)
	(b) pre-Cambrian Pikes Peak Granite	fluorite as accessory mineral	—	Mathews (1900)
	(c) Tertiary veins	fluorite	—	Cox (1945)
5. Crystal Park, Florissant, Teller Co., Colo.	pre-Cambrian pegmatites	fluorite, topaz	allanite	White (1935)
6. Petaca District, Rio Arriba Co., N.M.	pre-Cambrian pegmatites	fluorite	monazite, samarskite and rare fergusonite, gadolinite, yttrotantalite	Jahns (1946 A)
7. Ojo Caliente District, Rio Arriba Co., N.M.	pre-Cambrian pegmatites	fluorite	monazite, samarskite	Jahns (1946 A)
8. Elk Mountain District, San Miguel Co., N.M.	pre-Cambrian pegmatites	fluorite	monazite, samarskite, gadolinite, and possibly euxenite and fergusonite	Jahns (1946 A)
9. Pidlite pegmatite, southern Mora Co., N.M.	pre-Cambrian pegmatites	fluorite, topaz	monazite, cyrtolite?, gadolinite?, betafite, hatchettolite	Jahns (1946 B)
10. Humboldt Range, Nevada	scheelite pegmatite	fluorite	—	Kerr (1935)
11. Baringer Hill, Texas	pre-Cambrian pegmatite	fluorite	allanite, gadolinite, fergusonite, cyrtolite	Landes (1932)
12. Sheahan Quarry, Graniteville, Mo.	pegmatites	fluorite, topaz	—	Tolman and Goldich (1935)

TABLE 1.—(Continued)

District	Host Rocks	Fluorine Minerals	Rare Earth Minerals	Reference
13. Amelia District, Va.	pegmatites	fluorite, var. chlorophane	monazite; cyrtolite reported	Glass (1935)
14. Collins Hill, Middletown, Conn.	pegmatites	fluorite	—	Shaub (1946)
15. Branchville, Conn.	pegmatite	fluorite	cyrtolite	Shainin (1946)
16. Rockport, Mass.	segregation pegmatites in alkali granite	fluorite, yttrocerite	fergusonite, gadolinite, yttrocerite	McKinstry (1921)
17. Conway, N.H.	segregation pegmatites in granite	fluorite	allanite	Gillson (1927)
18. Quebec and Ontario, Canada	pre-Cambrian granitic pegmatites	fluorite	allanite, monazite, euxenite, rare earth-bearing uraninite	Spence (1930) Ellsworth (1931)
19. Cardiff Twsp., Ontario, Canada	pre-Cambrian syenitic pegmatites	fluorite (very abundant)	allanite, euxenite, ellsworthite	Spence (1930)
20. Ontario and Quebec, Canada	pyroxene-bearing pegmatites	fluorite	allanite, cenosite, rare earth zircon	Spence (1930)
21. New Ross, Nova Scotia	segregation pegmatites in granite	fluorite	monazite	Spence (1930)
22. Southeastern Manitoba, Canada	pegmatites	fluorite	monazite and rare earth-bearing uraninite	Spence (1930) DeLury and Ellsworth (1931)

In North America many pegmatites that contain fluorite also contain rare earth minerals. However, rare earth-bearing pegmatites do not always contain fluorite. Although the study of the pegmatite deposits of this continent is far from complete and the literature is scanty for many districts, this association of fluorite with rare earth elements does not appear to be merely coincidental. Rare earth elements have been detected in fluorites from many different localities: yttrium and ytterbium by Humphreys (1904); samarium and yttrium by Tanaka (1924); yttrium in Amelia, Virginia fluorite by Wherry (1929); europium and ytterbium by Haberlandt, Karlik, and Przibram (1934); lanthanum, cerium, yttrium, and erbium by Ho (1935); samarium by Przibram (1937); cerium and lutecium by Aspland, Brammall, and Leech (1938); and yttrium, lanthanum, cerium, and neodymium by Bray (1942). The low temperature fluorescence of fluorite is considered to result from their content of the bivalent rare earth elements (Przibram, 1937, and Haberlandt, Karlik, and Przibram, 1935). It is interesting to note that in commercial spectrographic analysis of 425 miscellaneous rock and mineral samples by the Laucks Laboratories (Freeman, 1942) a rare earth element (yttrium) was detected in only one sample—this being vein material "determined to be about 50 per cent fluorite and 40 per cent quartz" (sic).

CONCLUSIONS

1. In the Trout Creek Pass-Cotopaxi pegmatite district fluorite is associated with the rare earth minerals euxenite, monazite, allanite, and gadolinite. The pegmatites were formed in two stages: a magmatic stage in which microcline, quartz, and magnetite crystallized and a hydrothermal stage during which the other minerals were formed.

2. In North America pegmatitic fluorite appears chiefly in those deposits that also contain rare earth minerals. This geochemical association is probably not fortuitous, for fluorites from a variety of geological environments and many localities are known to contain rare earth elements.

REFERENCES

1. Aspland, U. L., Brammall, A., and Leech, J. G. C. (1938): *Am. Mineral.*, **23**, 415.
2. Bray, Joseph M. (1942): *Am. Mineral.* **27**, 769–775.
3. Cox, Doak C. (1945): *Colo. Sci. Sco., Proc.*, **14**, 263–285.
4. Cross, Whitman, and Hillebrand, W. F. (1885): *U. S. Geol. Survey, Bull.* **20**, 13–39.
5. DeLury, Justin S., and Ellsworth, H. V. (1931): *Am. Mineral.*, **16**, 569–575.
6. Ellsworth, H. V. (1931): *Am. Mineral.*, **16**, 576–579.
7. Freeman, Gerald O. (1942): *Am. Mineral.*, **27**, 776–779.
8. Gillson, Joseph L. (1927): *Am. Mineral.*, **12**, 307–319.
9. Glass, Jewell J. (1935): *Am. Mineral.*, **20**, 741–768.
10. Goddard, Edwin N., and Glass, Jewell J. (1940): *Am. Mineral.*, **25**, 381–404.
11. Haberlandt, Herbert, Karlik, Berta, and Przibram, Karl (1934): *Sitzber. Akad. Wiss. Wien. Math.-naturw. Klasse, Abt. IIa*, **143**, 151–160.
12. ——— *Sitzber. Akad. Wiss. Wien, Math.-naturw. Klasse, Abt. IIa*, **144**, 135–140.
13. Hanley, John B. (1946): *Am. Mineral.*, **31**, 197.
14. Heinrich, E. Wm. (1942): Manuscript report in files, *U. S. Geol. Survey.*
15. Ho, T. L. (1935): *Geol. Soc. China, Bull.* **14**, 279–282.
16. Jahns, Richard H. (1946A): *New Mexico Bureau Mines and Min. Res., Bull.* **25**.
17. ——— (1946B): *Bull. Geol. Soc. Am.*, **57**, 1208.
18. Kerr, Paul F. (1935): *Am. Mineral.*, **20**, 207.
19. Landes, K. K. (1932): *Am. Mineral.*, **17**, 381–390.
20. Landes, K. K. (1934): *Econ. Geol.*, **29**, 697–702.
21. Mathews, E. B. (1900): *Jour. Geol.*, **8**, 214–240.
22. McKinstry, H. E. (1921): *Am. Mineral.*, **6**, 56–60.
23. Over, Edwin, Jr. (1929): *Rocks and Minerals*, **4**, 106–107.
24. Palache, Charles, Berman, Harry, and Frondel, Clifford (1944): *Dana's System of Mineralogy*, p. 791.
25. Przibram, Karl (1937): *Zeit. Physik*, **107**, 709–712.
26. Shainin, Vincent E. (1946); *Am. Mineral.*, **31**, 329–345.
27. Shaub, B. J. (1946); *Am. Mineral.*, **31**, 512.
28. Spence, Hugh S. (1930): *Am. Mineral.*, **15**, 430–450, 474–496.
29. Switzer, George (1939): *Am. Mineral.*, **24**, 791–809.
30. Tanaka, T. (1924): *Jour. Opt. Soc. Am.* and *Rev. Sci. Instr.*, **8**, 501–510.
31. Tolman, Carl, and Goldich, Samuel S. (1935): *Am. Mineral.*, **20**, 229–239.
32. Wherry, Edgar T. (1929): *Am. Mineral.*, **14**, 299–308.
33. White, George M. (1935): *Rocks and Minerals*, **10**, 184–187.

STRUCTURE-PHASES IN THE SILICATE GLASS SYSTEM: $CaO \cdot Na_2O \cdot SiO_2$[1,2]

Joseph S. Lukesh,[3]

Crystallographic Laboratory, Department of Geology, Massachusetts Institute of Technology, Cambridge, Massachusetts.

Abstract

When the data for the total and species densities of soda-lime-silica glasses are plotted as functions of the ratios of sodium and calcium atoms to oxygen, they are found to fall on a three-dimensional diagram whose surface is made up of planes. The planes are bounded by straight lines which join rational compositions called "structure-phases." The data are interpretable as indicating that the structure-phases are those compositions in which the ratios of silicon to oxygen atoms are those for crystalline silicate structural types such as mica, amphibole, and pyroxene.

Introduction

The writer has pointed out elsewhere (2) that plots of the density of atomic species in silicate glasses as a function of the ratio of the metal atoms to oxygen atoms are essentially phase diagrams inasmuch as they reveal compositional regions in which the density follows well-defined laws and which are bounded by rational compositions. Since these compositions are not phases in the generally accepted physical chemical sense, it was proposed to call them "structure-phases," a term which implies the influence of the structure of the silicon-oxygen framework on the rate of change of the density. Huggins (1), who first investigated the variation of density with the ratio of metal to oxygen atoms, pointed out that the data could be represented by straight lines with changes in slope at the specific ratios of silicon to oxygen atoms that characterize crystalline silicate structural types. From Huggins' work and that of the writer (2), the structural control of the positions of the boundaries seems well established.

The early work of Huggins was concerned with the variation in the volume per gram atom of oxygen with the ratios of sodium and silicon atoms to oxygen. The writer showed that, not only are the computations much simplified, but also a great deal more information may be obtained if the densities of the atomic species are considered. It was found, for

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[1] Sponsored by the Owens-Illinois Glass Company.

[2] From an address, "The Application of Crystal Chemical Principles to the Problem of Glass Structure," read before *The Crystallographic Society of America*, Annapolis, Maryland, March 19, 1947.

[3] Now at: Research Laboratory, General Electric Company, Schenectady, N. Y.

instance, that the packing laws of the sodium atoms differ from those of the silicon-oxygen framework. Whereas the rate of change of the density of sodium shows discontinuities at all of the ratios representing crystalline types, as well as one for which no crystalline analogue is known, that of the framework shows only the last named discontinuity. It was suggested that this discontinuity represents saturation of the essentially cristobalite-like structure of the framework with sodium atoms.

That the data on density—and a number of other physical properties, as well—can be represented for a two-component system by a series of straight lines with discontinuities at points which have structural significance is of particular value since the positions of the discontinuities are independent of the metallic species present and represent changes in the linkage of the tetrahedrons of silicon and oxygen atoms. In studying a two-component system for the effect of the addition of a constant amount of a third component, one need only determine the slopes of the lines and their positions along the vertical scale. In the work previously referred to (2), it was suggested that the structure-phase diagram of a three-component system should be characterized by surfaces made up of planes. It is the purpose of this communication to consider this possibility in the three-component system $CaO \cdot Na_2O \cdot SiO_2$. Unfortunately, available published data are not particularly well adapted to this work and, although

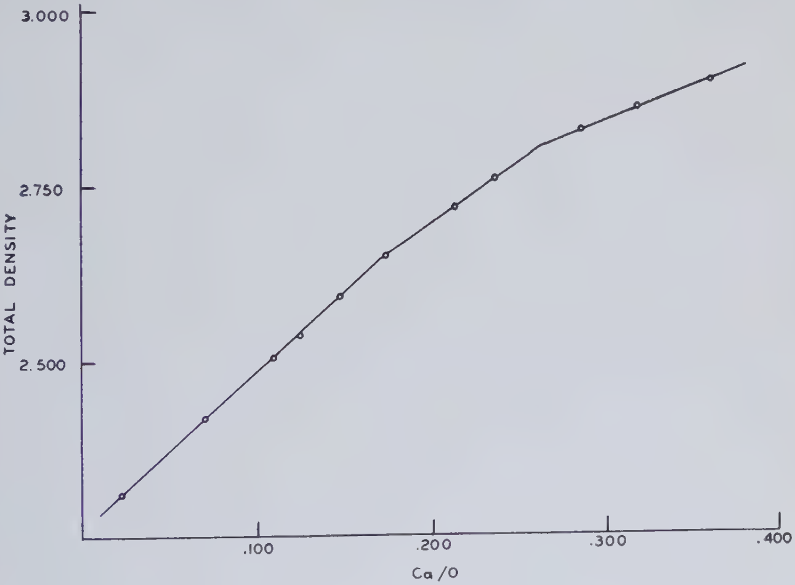

FIG. 1. Section through the structure-phase diagram of the total density in the system: $CaO \cdot Na_2O \cdot SiO_2$. Ratio Na/O constant.

the general theory appears to have been confirmed, many of the conclusions must be considered tentative.

EXPERIMENTAL

The data for a series of sodium calcium silicate glasses prepared by Morey and Merwin (3) have been plotted as functions of the two variables, Na/O and Ca/O, expressed as numbers of atoms. This results in a three-dimensional graph which, according to theory, should have a surface consisting of planes. Both the total density and the species density of the silicon-oxygen framework have been so treated. To test whether the surface is actually made up of planes, one may pass a section through the graph and plot any observed densities which fall along the line of the section. The observed values should, of course, lie along one or more straight lines. That this is the case is shown in Fig. 1, which is the plot of the densities which lie along a section of constant Na/O content in the structure-phase diagram constructed from the total density. Other sections, crossing the graphs in various directions, confirm the planar nature of the surfaces.

In order to determine the locations of the intersections of the planes, a number of sections have been constructed and the positions of the discontinuities plotted. Because the compositions of the glasses were not chosen for this purpose, it is only coincidental that a number of observed data happen to fall along a straight line. In order to collect enough data on the positions of the discontinuities so as to locate the boundaries, it was necessary to include points somewhat off the lines of the sections. Inclusion of such points makes the precise location of the discontinuity in any one section uncertain. However, in those cases in which a number of observed discontinuities fall along a straight line, it may be assumed that the boundary is accurately located.

Since the data do not permit accurate location of all of the boundaries by sectioning, it is necessary to consider other methods. One of these is to contour the surface. If the surface of the structure-phase diagram is made up of planes, the contours should be straight lines, with changes in direction at the boundaries. Contours drawn through points of equal density are, indeed, straight lines in the areas outlined by sectioning. The directions of the lines are the same within an area and slightly different in adjacent areas. The positions of the changes in direction may be taken as additional boundaries. Both the total density and the framework density can be well represented by straight line contours.

Information obtained from the sections and contours have been combined into consistent patterns of planes intersecting in straight lines. These are shown in Figs. 2 and 3, which are the plan views of the three-

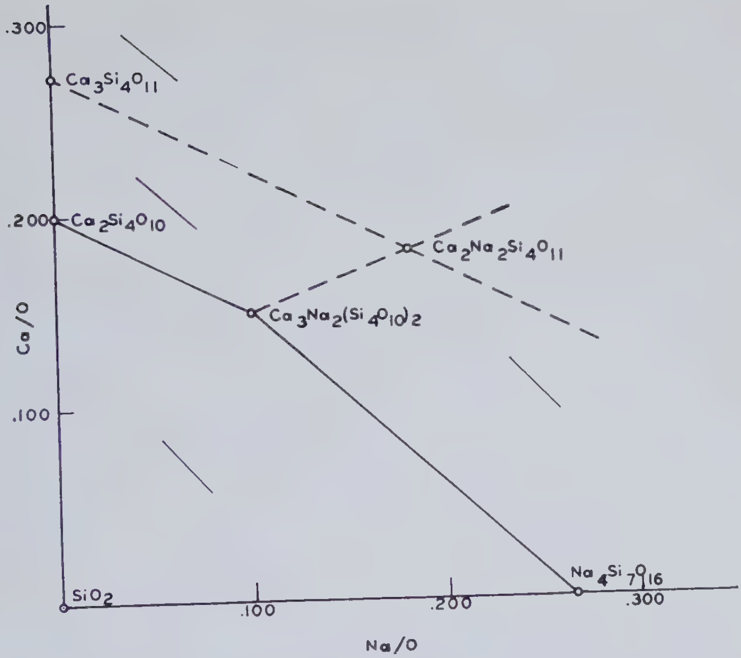

FIG. 2. Plan view of the tentative structure-phase diagram of the framework density in the system: $CaO \cdot Na_2O \cdot SiO_2$. Short lines in each field indicate directions of straight line contours of equal density.

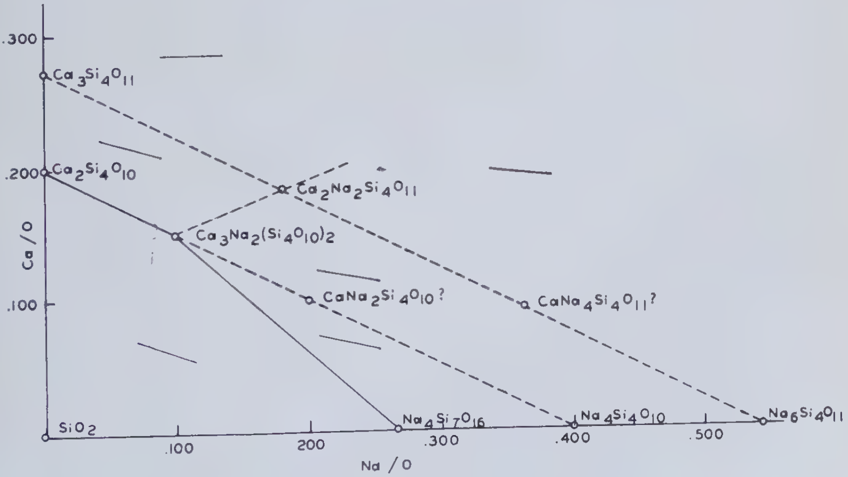

FIG. 3. Plan view of the tentative structure-phase diagram of the total density in the system: $CaO \cdot Na_2O \cdot SiO_2$. Short lines in each field indicate directions of straight line contours of equal density.

dimensional diagrams in which the density is the vertical axis normal to the plane of the paper. Directions of the contours are indicated. Solid lines represent boundaries which appear to have been located with some certainty; dotted lines are either less well determined or, in some cases, inferred. It must be emphasized that the conclusions reached in the present work are based on incomplete data and cannot be considered as final.

DISCUSSION

The Structure-Phase Diagram of the Silicon-Oxygen Framework Density: In the structure-phase diagram of the framework of pure sodium silicate glass, only one discontinuity appears and this is at the ratio Na/O = .268. In the three-component system, $CaO \cdot Na_2O \cdot SiO_2$, the axis, Ca/O = 0, is, therefore, divided into two fields which join at one structure-phase. In the earlier work (2), it was suggested that the existence of this phase, which does not have a crystal structure analogue, could be explained as representing saturation of the cristobalite-like structure of the framework with sodium atoms. A unit cell of cristobalite contains void space sufficient to house four sodium atoms and, since there are sixteen oxygen atoms in a unit cell of cristobalite, the sodium to oxygen ratio of the saturated structure would be 4/16 or .250, which is close to the observed value of .268. The rational composition is $Na_4Si_7O_{16}$.

If it may be assumed that the calcium atom, which is approximately the same diameter as the sodium atom, enters the structure in the same, or a similar, manner to sodium, the phase representing saturation would be expected to follow the straight line Na/O + Ca/O = .250. Examination of Fig. 2 reveals that the boundary starting at Na/O = .268, Ca/O = 0, does actually follow the predicted line. This boundary is the one for which the most data are available and may be considered to be the most accurately located of all the boundaries on the structure-phase diagram. The observed boundary does not, however, appear to follow the theoretical line the entire distance to Na/O = 0, Ca/O = .250. This is understandable, since the doubly charged calcium atom need not necessarily behave in the same manner as the singly charged sodium atom.

Data on the two-component system, $CaO \cdot SiO_2$, are insufficient to permit the construction of its structure-phase diagram. However, the observed boundaries in the three-component system can be extrapolated to Na/O = 0. The extrapolation must be guided by theoretical considerations since the boundaries are not clearly defined by either sections or contours. The known influence of the specific compositions of crystalline silicates in other two-component systems suggests that, by analogy, structure-phases may be expected at the same compositions in the calcium silicate system. Actually, the observed data can be extrapolated to points close to $Ca/O = .200$ and $.273$. These ratios represent the compositions $Ca_2Si_4O_{10}$ and $Ca_3Si_4O_{11}$, respectively, which are the mica and amphibole structural types. What data exist for the pure calcium silicate system are compatible with straight lines having changes in slope at these points.

If the influence of the structural type, $Ca_2Si_4O_{10}$, is admitted and if a line is drawn representing the composition, $Ca_xNa_ySi_4O_{10}$, an intersection is found with the previously located saturation boundary at the point, $Ca/O = .150$, $Na/O = .100$. The observed data from sections are consistent with such a line. The composition at the intersection is a rational one, being $Ca_3Na_2(Si_4O_{10})_2$. This represents the replacement of one quarter of the calcium atoms of $Ca_2Si_4O_{10}$ by an electrostatically equivalent number of sodium atoms. It also represents the composition at which the framework becomes saturated with metal atoms.

Following the same reasoning as in the previous case, one may draw a line representing the composition $Ca_xNa_ySi_4O_{11}$. The discontinuities observed in sections through this region are consistent with such a line, but the agreement is not convincing. Data, particularly that obtained from contours, indicate that this line is intersected by one from the composition $Ca_3Na_2(Si_4O_{10})_2$ near the point, $Ca/O = .182$, $Na/O = .182$. This is again a rational composition and represents the replacement of one half of the calcium atoms by the electrostatic equivalent of sodium. The composition is, therefore, $Ca_2Na_2Si_4O_{11}$.

The remainder of the diagram has been constructed mainly from inference and it will not be discussed. The observed species densities can, however, be represented by straight line contours in the various fields.

The Structure-Phase Diagram of the Total Density: Since the total density of the sodium silicate system shows discontinuities at the Na/O ratios of .268, .400, .545, and .667, there are boundaries starting at all of these points in the three-component system. With the exception of that starting at .268, these boundaries can logically be expected to follow rational compositions. For those at .400 and .545, respectively, the compositions are $Ca_xNa_ySi_4O_{10}$ and $Ca_xNa_ySi_4O_{11}$. (No data are available to show the existence of a boundary starting at .667 and following the line $Ca_xNa_ySiO_3$, although such a boundary might well be expected.) The boundary starting at .268 follows the saturation line until it intersects with that representing $Ca_xNa_ySi_4O_{10}$, as in the case of the framework density. The structure-phase diagram of the total density, while tentative, is consistent with observed data, which can be represented by straight line contours in the various fields. It is of interest to note that the contours in the region above $Ca/O = .273$ and between $Na/O = 0$ and about .200 are parallel to the sodium axis. This means that, for constant Ca/O, the addition of sodium to the glass has no effect on the total density.

Structure-Phases Deduced from the Diagrams: On the basis of Figs. 2 and 3, one may conclude, tentatively, that the rational compositions—structure-phases—listed in Table 1 are of structural importance in the three-component system $CaO \cdot Na_2O \cdot SiO_2$. The structure-phases are joined by straight lines, which are the boundaries of areas in which the surface of the solid diagram is planar. Those boundaries which follow rational compositions may themselves be looked upon as being structure-phases. In any one field, the density varies as a straight line in any direction, a fact which is of practical as well as theoretical significance.

TABLE 1. RATIONAL COMPOSITIONS OF STRUCTURAL IMPORTANCE

SiO_2	$Na_4Si_7O_{16}$	$Ca_2Si_4O_{10}$	$Ca_3Na_2(Si_4O_{10})_2$
	$Na_4Si_4O_{10}$	$Ca_3Si_4O_{11}$	$CaNa_2Si_4O_{10}$?
	$Na_6Si_4O_{11}$		$Ca_2Na_2Si_4O_{11}$
			$CaNa_4Si_4O_{11}$?

CONCLUSIONS

As has been emphasized, many of the structure-phases listed in Table 1 must be considered as tentative. While it is true that the data can be represented adequately by such planes as are outlined in the diagrams, Figs. 2 and 3, the exact locations of the boundaries have been guided in part by theoretical considerations. An exception to this is the boundary which represents saturation of the framework. Eight individual sections crossing this line revealed discontinuities in the proper positions. The field delineated this line and, probably, that representing the composition $Ca_xNa_ySi_4O_{10}$ can be considered as being well established. In this field, the framework is essentially cristobalite-like, with sodium and calcium atoms in the interstices. (The validity of including the region of low Ca/O ratio and very low Na/O ratio is open to question. It is in this region that the melt consists of two liquids and homogeneous glasses cannot be made.)

It would be desirable to prepare a series of glasses of specially selected compositions which will cover the structure-phase diagram with a grid of observed values. Data will lie on straight lines, and one should be able to determine the boundaries with accuracy. Until such time, no theoretical interpretation of the diagrams is possible.

Whatever the compositions of the structure-phases may be or their theoretical interpretation, the fact that the data can be well represented by planes is of practical value in the study of glass systems. The boundaries of the planes are dependent upon the manner of linkage of the silicon-oxygen tetrahedrons. The effects of other modifying metals can be determined with a minimum of experimental effort, since the attitude of a plane can be determined from three points. In addition to specific gravity studies, the investigation of optical properties will be facilitated. The close relation between index of refraction and density suggests, for instance, that the surface representing the refractive indices as functions of Ca/O and Na/O should be made up of planes, intersecting in the same boundaries. This appears to be the case with the data already studied.

REFERENCES

(1) HUGGINS, M. L., *Jour. opt. Soc. Am.*, **30,** 420 (1940).
(2) LUKESH, JOSEPH S., *Science*, **104,** 199 (1946).
(3) MOREY, G. W., AND MERWIN, H. E., *Jour. opt. Soc. Am.*, **22,** 632 (1932).

NEW DATA ON ELPASOLITE AND HAGEMANNITE*

CLIFFORD FRONDEL,
Harvard University, Cambridge, Massachusetts.

ABSTRACT

Restudy of type elpasolite of Cross and Hillebrand (1885) proves it to be a species distinct from cryolite and identical with artificial K_2NaAlF_6. Isometric, simple cell, with $a_o = 8.093$ and cell contents $K_8Na_4Al_4F_{24}$. Hardness $2\frac{1}{2}$; specific gravity 2.995 (obs.), 3.015 (calc.). No cleavage, fracture uneven. Colorless, with the luster of cryolite. Isotropic, with $n = 1.376 \pm 0.002$.

Hagemannite of Shepard (1866) from Ivigtut is shown to be a variable mixture of ralstonite and thomsenolite pigmented with iron oxide.

ELPASOLITE

Elpasolite was tentatively described by Cross and Hillebrand (1) in 1883 as a new aluminofluoride of sodium and potassium. The mineral occurred very sparingly with cryolite, pachnolite, thomsenolite, prosopite and gearksutite in vein-like bodies of quartz and microcline in the Pikes Peak granite at St. Peter's Dome, at the southern base of Pikes Peak, El Paso Co., Colorado. The cryolite was the original deposit and the other minerals, as at Ivigtut, were derived by alteration either directly therefrom or from other, earlier-formed, secondary fluorides.

Through the courtesy of Dr. W. F. Foshag, the original analyzed specimen of Cross and Hillebrand, preserved in the type collection of the U. S. National Museum, was made available for study. The elpasolite forms indistinct aggregates of crystals ranging up to 0.5 mm. in size lining solution cavities in massive pachnolite. A little powdery gearksutite is present on the specimen and is formed later than the elpasolite. No recognizable or measureable crystal faces were observed on the elpasolite, although Cross and Hillebrand state that they saw a few crystals with a semblance of cube and octahedral faces. The mineral is quite isotropic and has an index of refraction of 1.376 ± 0.002. The specific gravity as measured on the microbalance is 2.995 ± 0.01. The hardness is $2\frac{1}{2}$. Cleavage is lacking and the fracture is uneven. Fragments are colorless and have the weak vitreous to slightly greasy luster typical of cryolite.

The x-ray powder diffraction pattern, given in Table 1, was completely indexed in terms of an isometric, simple cell with $a_0 = 8.093$. The pattern differs entirely from that of the two isometric aluminofluorides ralstonite and cryolithionite, and from that of cryolite, thomsenolite, pachnolite, prosopite, gearksutite, chiolite and fluellite. Specimens of weberite and

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* Contribution from the Department of Mineralogy and Petrography, Harvard University, No. 291.

TABLE 1. *X*-RAY POWDER DIFFRACTION DATA FOR ELPASOLITE

Cu radiation, Ni filter

d obs.	*d calc.*	*I*	*hkl*	*d obs.*	*d calc.*	*I*	*hkl*
4.655	4.673	1	111	1.132	1.133	1	551 711
4.000	4.047	0.5	200	1.080	1.082	3	642
2.863	2.862	10	220	1.053	1.054	0.5	731 553
2.336	2.336	8	222	1.013	1.012	2	800
2.237	2.244	0.5	320	.955	.954	3	660 882
2.024	2.023	10	400	.928	.928	1	662
1.846	1.852	1	331	.905	.905	5	840
1.650	1.652	4	422	.889	.888	0.5	911 753
1.578	1.587	0.5	510 431	.863	.863	3	664
1.556	1.558	2	511	.849	.848	0.5	931
1.428	1.431	6	440	α_1 .827	.826	4	844
1.367	1.368	0.5	531	α_2 .827	.826		
1.277	1.280	3	620	α_1 .795	.793	6	10.2.0 852
1.220	1.220	2	622	α_2 .793	.793		
1.168	1.168	3	444				

jarlite = metajarlite were not available, but the reported properties of these minerals do not suggest any relation to the mineral at hand. There is a certain relation between the powder patterns of elpasolite and cryolite, however, in that most of the stronger lines in the latter correspond roughly in position and intensity to strong lines in the former pattern. Cryolite, Na_3AlF_6, is markedly pseudoisometric in many characters, although strictly monoclinic in crystallization, and as appears beyond belongs in the same formula-type as elpasolite.

The powder spacing data for elpasolite are found to correspond except for a very slight difference in cell dimensions to that given by Náray-Szabó and György (2) for the artificial compound K_2NaAlF_6 found by them in a study of the melt system Na_3AlF_6—K_3AlF_6. Earlier, Menzer (3) reported that artificial K_2NaAlF_6 formed by evaporation of a dilute solution containing KF, NaF and $Al_2(SO_4)_3$ was simple cubic with $a_0 = 8.09 \pm 0.02$, but the spacing data are not given. The cell contents found were $K_8Na_4Al_4F_{24}$. His material appeared as small octahedra with subordinate cube faces.

The original analysis of elpasolite by Hillebrand is cited in Table 2.

The K and Na determinations were said by Hillebrand to be only approximations. H_2O was shown to be absent. F was not directly determined, although shown to be present in large amount, and the value given here is calculated in amount necessary to satisfy the bases present. The cell contents calculated from this analysis, with the exception of the value for Al, diverge somewhat from the values $K_8Na_4Al_4F_{24}$ expected from the indicated identity with the artificial compound. The specific gravity calculated on the basis of the expected cell contents, 3.015, is in satisfactory agreement, however, with the observed value, 2.995, while the value calculated from the actual analysis, 2.969, is relatively low. The observed divergences thus appear to be due to the admitted analytical error.

TABLE 2. CELL CONTENTS OF ELPASOLITE

Analysis		Atomic quotients	Measured cell contents (M.W.=969.5)	Theoretical cell contents
Al	11.32	0.4197	4.070	4
Ca	0.72	0.0180	0.174	
Mg	0.22	0.0090	0.009	
K	28.94	0.7402	7.176	8
Na	9.90	0.4405	4.271	4
F	47.90	2.521	24.44	24
	99.00			

HAGEMANNITE

In connection with the study of elpasolite, an examination was made of the ill-defined mineral hagemannite from Ivigtut, Greenland. This substance was described by C. U. Shepard (4) in 1866 on the basis of an analysis by Hagemann as a new fluoride of Na, Ca, Mg, Al and Fe. It occurs as dull, ocher- to wax-yellow or brown crusts and veinlets with a compact structure much resembling yellow jasper. The specimens available comprised corroded masses of cryolite coated with drusy crystals of thomsenolite, ralstonite and pachnolite which were locally covered over by thick crusts of hagemannite. The crusts have a crude concentric layering or colloform structure and the grain size and color varies noticeably in successive layers. Dense jaspery material on several specimens, seemingly homogeneous to the unaided eye, were found on optical and x-ray study to consist of very fine grained ralstonite admixed with small amounts of thomsenolite. Minute amounts of several unidentified minerals also were present. The ralstonite had an index of refraction of 1.418

and a specific gravity of 2.60. Other layers in the crusts, somewhat more coarsely grained and lighter colored, were found to consist in large part of thomsenolite. Complete gradations occur between ralstonite-rich and thomsenolite-rich mixtures. Pure thomsenolite itself sometimes occurs at Ivigtut as white, opaline to chalcedonic masses. Locally, thin films of an ocherous yellow-brown iron oxide, doubtless goethite, are present in the hagemannite and the same substance occurs sparingly disseminated through the crusts as a pigmenting material. Hagemannite thus is a variable mixture of ralstonite, thomsenolite and goethite. The original analysis apparently was made on material relatively high in thomsenolite. The identity of this analysis with thomsenolite (or pachnolite) after deducting Fe, Mg and Si as impurities was early suggested by Groth (5).

The writer wishes to acknowledge the assistance of Miss Mary Mrose during the course of the work.

REFERENCES

1. CROSS AND HILLEBRAND: *U. S. Geol. Surv., Bull.* **20,** 57 (1883).
2. NÁRAY-SZABÓ AND GYÖRGY: *Matem. Termes. Ert.*, **60,** 364 (1941).
3. MENZER: *Fortschr. Min.*, **17,** 61 (1932).
4. SHEPARD: *Am. Jour. Sci.*, **41,** 246 (1866).
5. GROTH: *Zeits. Kryst.*, **7,** 480 (1883).

NOTES AND NEWS

SULFUR AS A MOUNTING MEDIUM FOR POLISHED SECTIONS

George J. Neuerburg, *University of Idaho, Moscow, Idaho.*

To investigate the semi-quantitative effects of polishing on opaque mineral optical figures, polished oriented sections of crystals were made. The majority of such crystals were small. Without suitable equipment, the problem of holding the crystals in the preferred orientation during mounting became a serious one.

Mounting such crystals in bakelite in a hydraulic press is out of the question in most cases, especially when a study of a surface parallel to (001) on an acicular crystal is desired. Holding such crystals in position, during mounting, with tweezers is satisfactory, but requires an open air mold and a mounting medium which is readily fusible and which hardens quickly.

Molds of $\frac{1}{2}''$ diameter glass tubing, $\frac{1}{2}''$ to $\frac{3}{4}''$ long have been employed but molds of any material should be suitable for this work.

As a mounting medium red sealing wax was first used. This was found to be a most unsatisfactory mounting medium, primarily because it has a strong tendency to drag during the polishing process and to pit soft minerals and those minerals having good cleavages. Furthermore, sealing wax tends to become frothy when melted and not sufficiently fluid to readily fill all open spaces.

It was felt that a satisfactory mounting medium should meet essentially the following conditions: (1) it should have a minimum tendency to drag during polishing; (2) its melting point should be low enough that it will not alter the mineral, and high enough so that it will not melt from the heat of friction developed in polishing; (3) it should be readily available and cheap; and (4) it should become fluid enough on melting to fill all open spaces and should melt quietly without the formation of bubbles.

Several materials were tried without notable success. An alloy of 60% Bi, 40% Cd is suitable except for item 3 and the strong tendency to form an oxide crust on melting. Common tin solder has too high a melting point and such a high specific gravity that it floats many of the minerals to be mounted.

Sulfur was tried as a mounting medium at the suggestion of Roy Anderson, University of Idaho. This substance most nearly fulfills the conditions outlined above. It has one drawback in that the operation must be carried out under a hood because of the noxious fumes given off.

In preparing the mount, the crystal to be polished is placed in position on a glass plate and the mold placed around it. Powdered sulfur is melted in an evaporating dish over a Bunsen burner. When molten, it is allowed to stand for a few minutes, with a cover on the dish. This is done to extinguish the burning sulfur fumes and because it has been found that the molten sulfur is more fluid when this is done than when it is first taken off the flame. The sulfur is then poured into the mold and left to harden. It becomes sufficiently hard to hold the crystal in position in a matter of a few seconds; therefore, it is necessary to hold the crystal in position with tweezers but a few seconds.

In the final stages of polishing, the sulfur mount usually becomes loosened from the glass tube and falls out. If desired, this can be obviated by using brass tubing, which has been indented in the manner described by Short (*U.S.G.S.*, *Bull.* **914,** p. 9).

The mount finally obtained is brown in color and consists of relatively large, tightly interlocked crystals. The material fills all irregularities on the mineral specimen very satisfactorily.

An investigation into the possibility of using sulfur as a mounting medium in briquettes was made. Satisfactory results were not obtained. Sulfur becomes very fluid on heating under pressure and readily extrudes from the mold. Also, a uniform mount could not be obtained, apparently because of a disturbing effect from the mineral specimen; very commonly the mount was hard and crystalline everywhere except around the specimen, where it was powdery.

Briquettes of sulfur, using only pressure, were also made. Very similar results to those obtained when using heat and pressure together were obtained, though the briquettes were not quite as tough. The pressures used were of the order of 3000 to 4000 pounds.

There seems to be little doubt that careful experimentation with various combinations of pressure, time of heating, time of cooling, and time under pressure would yield a suitable sulfur briquette, but these conditions would probably involve more time than is used in preparing a bakelite briquette, and the product would probably offer no special advantages over the usual bakelite mount.

It is the author's intention to attempt to find a suitable mounting medium from which briquettes may be made by employing moderate pressures for a relatively short time, without the application of heat.

The author wishes to express his appreciation to Ray Kurtak, Chemist, Idaho Bureau of Mines and Geology, for his assistance while trying different mounting media. Also, he wishes to acknowledge aid in the preparation of specimens given him by Mr. F. L. Jackson and Mr. G. M. Glarborg, students in the School of Mines, University of Idaho.

NOTE ON QUANTITATIVE ANALYSIS BY X-RAY DIFFRACTION METHODS

KATHLEEN LONSDALE, *University College, London, England.*

In a recent paper ("Quantitative Mineral Analysis with a Recording *X*-ray Diffraction Spectrometer," *Am. Mineral.*, **32,** 508–517) Howard F. Carl has drawn attention to some of the factors limiting the usefulness of quantitative *x*-ray analysis by photographic methods. Undoubtedly sample preparation is one of the most critical problems whatever method is used. In preparing samples for "working curves" it appears from the paper that quartz powder was mixed with various other powdered materials in a range of concentrations. The record shown in Fig. 1. of the paper, if it is typical, would indicate that the powder used was finely divided, but that the particles were not small enough to show line broadening. It should be pointed out that considerable quantities of *colloidal* quartz, if mixed with other well crystallized materials, could be present and yet elude measurement, especially if well-crystallized quartz were also to be found in the mixture.

Howard F. Carl implies that variations in the *x*-ray output are more serious in the case of the photographic method than in that of the Geiger-counter spectrometer. That is surely not the case, however; such variations are likely to be *less* significant in the photographic method, which integrates the output over an appreciable time period, than in any method depending on the almost instantaneous output from a variable source, even if measurements are repeated several times. The fact that the standard commercial equipment used provided a very steady output, was a recommendation for that particular source of *x*-rays, but not evidence in favor of any particular method of measuring intensity.

The most surprising statement in the paper, however, is that in the case of the recording Geiger-counter *x*-ray spectrometer "there is only a linear relation between intensity and recorder deflection. This numerical value of line height is, under standardized conditions, a direct measure of the actual intensity of the diffracted beam from the specimen." No evidence is offered to show the correctness of this statement. Now it is possible to obtain a calibration curve for any individual recording spectrometer by repeating the same peak with an increasing number of Ni filters either between the *x*-ray tube and the specimen or, if more convenient, between the specimen and the Geiger-counter tube (the results are indistinguishable). Each filter, if 0.0006″ thick, should cut down the intensity by a factor of about 2, or if 0.001″ thick, by a factor of about 3. The accompanying graph (Fig. 1) shows the recorded peaks obtained in this way for 1, 2, 3, 4, 5, 6, 7 Ni filters each 0.001″ thick, and it is very obvious that the ratio of peak heights for n to $(n-1)$

filters is far from constant, as it ought to be if there were a linear relationship of intensity and recorder deflection. The high intensities (corresponding to a full scale deflection) are much lower than they ought to be relative to an intensity of medium value, and the low intensities (such as would be given by a colloidal specimen unless present in considerable quantity) are not recorded at all. A correct linear relationship was only found to exist over a very restricted portion of the graph (about 1–3 units) for any conditions of sensitivity or damping. The instrument ceased to record, even at highest sensitivity, at an intensity which was certainly more than 100 times the minimum intensity observable with a scaling circuit and mechanical impulse counter. Results similar to the above were found with various Geiger-counter tubes and under various conditions, but there is the possibility that different spectrometers may have different calibration curves, and therefore any quantitative analysis, to be of value, should be preceded by the measurement of the curve appropriate to the particular equipment used.

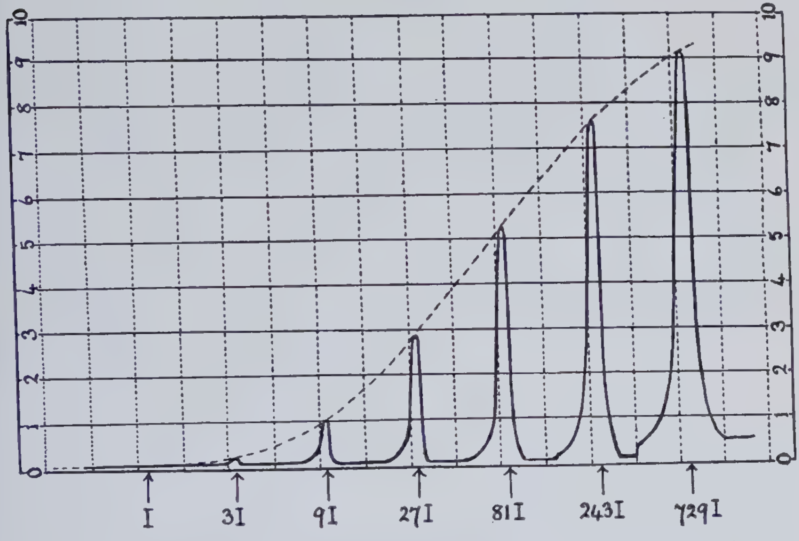

Fig. 1. Calibration curve for recording Geiger-counter spectrometer. For a linear relationship, each peak should be 3 times the height of the previous peak; this is only approximately true in the limited range 1–3 units. Similar curves were obtained under widely varying conditions.

Perhaps it should be pointed out that quantitative analysis by photographic methods equally requires care with regard to calibration of line blackening or density versus x-ray intensity. Mere matching against a "working curve" (that is, a set of lines corresponding to different concentrations of one constituent in a powder mixture) is not sufficient in the case where one or other constituent may be of colloidal dimensions or poorly crystallized.

LETTER TO THE EDITOR

Finland has an excellent and keenly scientific minded Technical Institute, Teknillinen Korkeakoulu. During the war its library was bombed and totally destroyed.

On my recent trip to Finland for the American Friends Service Committee, I discussed the situation with Dr. Martti Levon, Director of the Institute. He said he would welcome gifts of Scientific and Technical Books and Periodicals from America to take the place of those destroyed. In the remarkable efforts for recovery that the Finns are making, the lack of technical library facilities is a very serious handicap. It would be a practical act of friendship to a nation that holds America in high regard if Americans should contribute good technical books and periodicals to this library.

Any such gifts should be marked for the Institute of Technology, Helsinki, and sent to the Legation of Finland, 2144 Wyoming Ave., N.W., Washington, D. C. Dr. K. T. Jutila, the Finnish Minister, will arrange for their being shipped to Finland.

Sincerely yours,
ARTHUR E. MORGAN
Member, *American Friends Service Committee*
Yellow Springs, Ohio

MANUSCRIPT TRANSLATIONS FROM THE RUSSIAN

All geologic publications.—The Committee on Russian Literature of the Geological Society of America has begun the compilation of a list of translations from Russian into English of geologic papers and books; that is, a list of translations extant in manuscript form in the United States. Please send information as to any such translations to the committee chairman or to Geological Society headquarters. The word *geologic* is used here in its widest sense to extend inclusively from geophysics to paleontology.

Current geologic publications.—If information about translations of recent publications is received soon enough, it will be included in forthcoming volumes of the *Bibliography and Index of Geology Exclusive of North America* and the *Bibliography of Economic Geology*, subject to permission from proprietors of translations.

RONALD K. DEFORD, *Chairman*,
Box 1814, Midland, Texas.

To the list of United States triplite occurrences as presented in Table 1, page 521, in the September–October 1947 issue of the *American Mineralogist* (Triplite crystals from Colorado by C. W. Wolfe and E. Wm. Heinrich) there should be added the Rutherford pegmatite near Amelia, Virginia. This occurrence, which was recorded and described by Glass (*Am. Mineral.*, **20**, 759, 1935), was inadvertently omitted from the tabulation.

E. WM. HEINRICH

Correction

Dr. John P. Marble has called our attention to the fact that in our short article entitled "Polycrase in New York State" we omitted to cite his paper entitled "Possible Age of

Allanite From Whiteface Mountain, Essex County, New York" which appeared in the *American Journal of Science*, January 1943. Hence, the polycrase locality in the town of Day, New York, referred to in our paper is the third occurrence of radioactive minerals in the Precambrian of northern New York State.

EDWARD S. C. SMITH AND OSCAR R. KRUESI

The Industrial Diamond Information Bureau, Industrial Distributors (1946) Ltd., St. Andrew's House, 32–34, Holborn Viaduct, London, E.C. 1., publishes monthly a bulletin containing abstracts of articles dealing with properties and industrial applications of diamond together with notices of patents and patent applications in many States. A copy of this bulletin may be obtained, free of charge, on application to the above address.

The first Fall meeting of the New York Mineralogical club was held on Oct. 15, 1947, and was devoted to the collecting experiences of its members during the preceding summer. At this meeting fifteen members delivered talks on their activities which extended from Maine to Brazil, and many interesting specimens were displayed. Some collectors brought in a supply of minerals for distribution to other members.

MINERALS OF ARIZONA by FREDERIC W. GALBRAITH. Second edition (*revised*). Arizona Bureau of Mines, Geological Series No. 17, Bulletin No. **153** (1947); 102 pages. Price one dollar (free to residents of Arizona).

This is an enlargement and revision of Bulletin No. 149 which was issued in 1941 (see *Am. Mineral.*, **27**, 332). With additional information now available through the publication of vol. 1 of *Dana's System of Mineralogy* it was deemed desirable to issue the Bulletin on Minerals of Arizona in a revised and enlarged form. The mineral index now lists 431 names.

W.F.H.

A suggestion has been received that the Journal publish from time to time research projects under investigation and the names of the individuals involved. It was felt that such publication might prevent unfortunate duplication of effort, as such instances have occurred in the past, and further greater cooperation between individuals engaged on the same or similar investigations. The success of the effort will depend largely upon the extent to which this information is made available by the individuals concerned. The editor will gladly publish all data thus submitted.

Recent publications of interest to mineralogists and petrologists include The Pennsylvania State College Bulletin No. 47, Properties and New Uses of Pennsylvania Slate (price $2.00), and Arizona Bureau of Mines, Technology Series No. 42, Bulletin 154, Field Tests for the Common Metals (ninth edition), by George R. Fansett.

PROCEEDINGS OF SOCIETIES

MINERALOGICAL SOCIETY (LONDON)

A meeting of the Society was held on Thursday, November 6, 1947, in the apartments of the Geological Society of London, Burlington House, Piccadilly W. 1 (by kind permission). The program included an exhibit of a new two-circle optical goniometer by Mr. E. S. Marsh on behalf of Unicam Instruments, Ltd., Cambridge. The following papers were read: (Kindly furnished by G. F. Claringsbull, General Secretary).

(1) *The occurrence of an orthorhombic, high temperature form of Ca_2SiO_4 in the Scawt Hill contact zone, and as a constituent of slags.*

By Professor C. E. Tilley and Mr. H. C. G. Vincent.

An orthorhombic (pseudohexagonal) form of Ca_2SiO_4 occurs as a mineral phase associated with larnite, gehlenite, or spurrite assemblages at Scawt Hill. As a solid solution it is recognized as a major constituent of a group of spiegeleisen slags.

(2) *Earlier stages in the metamorphism of siliceous dolomites.*

By Professor C. E. Tilley.

Talc is recognized as a member of the series of index minerals characterizing the increasing decarbonation associated with the progressive thermal metamorphism of siliceous dolomite. In this series talc forms the initial phase and gives place with rising temperature to tremolite, two stages in the production of which are indicated. Illustrations are drawn from the outer aureole of the Beinn an Dubhaich granite of Skye.

(3) *Note on the occurrence of anatase in some fireclay deposits.*

By Dr. G. W. Brindley and Dr. K. Robinson.

Although chemical analyses of fireclays generally indicate a few per cent of TiO_2, the mineralogical form in which TiO_2 occurs is seldom given. A number of references to the observation of rutile needles suggests that rutile is the form in which the titania usually occurs. *X*-ray powder photographs, however, show that anatase is commonly present and rutile either absent or present in smaller quantities. The investigations have been confined to fireclays from the Millstone Grit series of Central Scotland and from the Coal Measures of Yorkshire. Sedimentation tests show that the anatase is present as very fine particles of the order of one micron.

(4) *An improved polarizing microscope. III. The slotted ocular and the slotted objective.*

By Dr. A. F. Hallimond and Mr. E. W. Taylor.

(5) *Biographical notices of mineralogists recently deceased. (Eighth series).*

By Dr. L. J. Spencer.

Previously published triennially, these have now been in abeyance since 1939. The present list is, therefore, much longer than usual and covers the period 1939–47. A selection has been limited to 87 lives, ranging in age from 26 to 90, with an average of 68.9 years. This year (1947) the Society has lost three past-Presidents.

BOOK REVIEWS

MINERALOGISCHE TABELLEN

(Im Auftrage der Deutschen Mineralogischen Gesellschaft) by Hugo Strunz.

Akademische Verlagsgesellschaft Becker & Erler Kom.-Ges. Leipzig 1941, pp. ix+287. Lithoprinted by Edward Brothers, Ann Arbor, Mich., by authority of the Alien Property Custodian (1944), Price, $7.25.

This is one of the most important mineralogical books published in recent years. It should have a place in every mineralogical and geological library.

The title of this book is somewhat misleading. One might expect it to consist of a series of determinative tables, but for the most part it is a systematic list of minerals. It is essentially a new edition of the well-known *Tabellarische Übersicht der Mineralien* by Paul von Groth (1st edition, 1874; 4th edition, 1898).

It has the same title as the *Mineralogische Tabellen* of Groth and Mieleitner, 1921, to whom the book is dedicated. The determinative tables of the latter (pp. 135–162) are omitted.

An important part of the book is the introductory fifty-six pages consisting: (A) of definitions and "Grundgesetze." Five fundamental laws of crystal geometry are recognized instead of the usual two or three. Four fundamental laws of crystal chemistry (I. isotypy; II. isomorphism; III. diadochy; and IV. polymorphism) are mentioned.

(B) Principles of Classification. Nine classes are given. These are enumerated later in the review.

(C) Important Structure Types. This is a well-illustrated summary of our present knowledge of the structure of crystals. Since names of authors and dates are given, it is easy to look up most of them in such a work as Wyckoff's *The Structure of Crystals.*

Following (C) is section (D), which consists of a number of tables showing (1) atomic radii plotted against atomic numbers, (2) chemical elements in alphabetical order with atomic weights, (3) the periodic system of elements, (4) a table of 32 crystal classes with six systems and not the seven of Groth. (The only gap in the list of representatives of the 32 classes is the trigonal bipyramidal class), (5) the 14 Bravais lattices, and (6) a table giving the 230 space-groups with both the Schoenflies symbols and the normalized Mauguin symbols.

The major portion of the book "Systematik der Mineralien auf kristallchemischer Grundlage" occupies 164 pages.

The divisions (Klasse) are:

I. Elements, alloys, carbids, nitrids, and phosphids.

II. Sulfids and related compounds including oxysulfids. (The sulfo-salts are not treated separately as in Groth's *Tabellarische Übersicht.*)

III. Halids.

IV. Oxids and hydroxids (and along with them arsenites, selenites, tellurites, and iodates).

V. Nitrates, carbonates, and borates.

VI. Sulfates, tellurates, chromates, molybdates, and tungstates.

VII. Phosphates, arsenates, and vanadates.

VIII. Silicates. The order of silicates is (A) discrete-silica silicates, (B) self-contained-group silicates, (C) chain silicates, (D) sheet silicates, and (E) net work silicates. This is the order preferred by the reviewer (see *Am. Mineral.*, **27,** 232, 1942). Strunz uses the names: (A) Nesosilikate, (B) Sorosilikate, (C) Inosilikate, (D) Phyllosilikate, and (E) Tektosilikate for these five groups. These names were coined by him in 1938 (*Zeit. f. die gesamte Naturwissenschaft*, 4 Jahrgang, 1938, p. 187).

It should be remarked that Strunz departs from Berman, Winchell, and others in treating quartz and the other silica minerals under the oxids rather than along with the feldspars in the network silicates. The reviewer agrees with the viewpoint of Strunz.

IX. Organic compounds, which include salts of organic acids and hydrocarbons.

This is followed by a combined index and alphabetical list of mineral names which occupies 62 pages. This seems to be fairly complete (*ca.* 5600 names), but I note the omission of such names as aegirine-augite, argentine, diopside-jadeite, geolyte, kalaite, lamprobolite, leptochlorite, metabrucite, oxyhornblende, pseudotridymite, pseudowollastonite, serpophite, and shanyavskite.

About 2000 minerals are given species rank.

At the end of the book there is a list of 41 mineralogical museums. Of American museums only Harvard, U. S. National Museum, American Museum of Natural History, Ottawa, Toronto, Brazilian National Museum, and Argentine National Museum are mentioned.

Among points upon which there may be disagreements with the author are the following:

Gibbsite is the name used for hydrous aluminum phosphate instead of for $Al(OH)_3$.

Mohavite is used instead of tincalconite.

Niobite is preferred to columbite.

Hydromagnesite is given as rhombic-bipyramidal. The reviewer proved (*Am. Jour. Sci.* **6,** 37–47, 1923) that it is monoclinic.

Grünerite is used instead of grunerite.

The formula of ankerite is given as $CaFe(CO_3)_2$. It should be $Ca(Mg,Fe)(CO_3)_2$.

Mineral groups, usually restricted to isomorphous series, are used in a wider sense than is customary. For example, hexagonal glaserite, monoclinic glauberite, and rhombic anhydrite are placed in the same group.

Some synthetic products are included along with the minerals. For example, some of the Tutton'sche salze $R^{I}_2R^{II}(SO_4)_2 \cdot 6H_2O$ are given along with the three minerals: schönite (picromerite), cyanochroite, and boussingaultite.

In the opinion of the reviewer the author has done an excellent job. It is a worthy successor of Groth's *Tabellarische Übersicht der Mineralien*. If is especially useful in view of the fact that only one volume of the new seventh edition of *Dana's System of Mineralogy* has yet appeared.

Austin F. Rogers, *Stanford University*

ROCKS AND ROCK MINERALS by Louis V. Person, third edition revised by Adolph Knopf. John Wiley and Sons, Inc. vii+349 pages (1947). Price $4.00.

The first edition of this popular book came out in 1908 and served beginners in the field of geology for many years. The second edition was published in 1926. The second and third (the present) editions were revised by Professor Knopf. In his preface Professor Knopf says "To simplify, clarify, and condense were the guiding principles in making the revision." In that he has succeeded to the extent that the prospector will find the book readily understood and serviceable.

The arrangement of subject matter is almost entirely retained as in the earlier editions — about eighty pages being devoted to mineral descriptions and two hundred thirty pages devoted to the petrology, description and classification of the various rock types. Determinative tables of minerals and rocks are included.

The discussion of the petrology of rock types is highly conventional. Currently controversial aspects are avoided as perhaps they should be, even at the hazard of giving the beginning student a picture of a fixed and completed study rather than one which is suffering severe growing pains. The statements on such topics as complementary dikes and the role of the critical temperature of water are carried forward from the earlier editions.

Though the subject matter has been little changed the text has been quite extensively rewritten to advantage. Several new analyses are added. If used as a class-room text, the subject matter can well be discussed further by the instructor, especially in the field of petrogenesis.

R. C. EMMONS, *University of Wisconsin*

JOINT CRYSTALLOGRAPHIC MEETING

The American Society for *X*-Ray and Electron Diffraction and the Crystallographic Society of America will hold their first joint meeting at Yale University, April 1st to 3rd inclusive, 1948. Joint and separate technical sessions will be held and the President of the Crystallographic Society will deliver his retiring address. Detailed notices have been sent to members of the two Societies. Non-members wishing further information may obtain it from either of the undersigned.

ELIZABETH A. WOOD, *Secretary,*
American Society for X-Ray and Electron Diffraction,
Bell Telephone Laboratories,
Murray Hill, New Jersey.

WILLIAM PARRISH, *Secretary,*
Crystallographic Society of America,
Philips Laboratories, Inc.,
Irvington-on-Hudson, New York.

NEW MINERAL NAMES

Johachidolite

Eiichi Iwase and Nobufusa Saito, Johachidolite: a new mineral, a hydrous fluoborate of sodium, calcium, and aluminum. *Sci. Papers Inst. Phys. Chem. Research Tokyo*, **39,** 300–304 (1942); through *Chem. Abs.*, **41,** 6173 (1947) and private communication of authors to W. F. Foshag.

Chemical Properties: Analysis gave SiO_2 0.34, Al_2O_3 28.34, Fe_2O_3 0.09, MnO 0.23, CaO 24.77, Na_2O 8.27, P_2O_5 0.03, B_2O_3 24.21, Cl none, F 12.21, H_2O- 0.07, H_2O+ 6.52, sum 105.08 less $(O=F_2)$ $5.14=99.94\%$. Rare earths are present, see below. The empirical formula deduced is $H_6Na_2Ca_3Al_4F_5B_6O_{20}$ (this does not balance—M.F.)

Physical and Optical Properties: Colorless, transparent. H. $6\frac{1}{2}$–7, G. slightly below 3.4. Optically biaxial, negative, n_D, alpha 1.715, beta 1.720, gamma 1.729 (Chem. Abs.), 1.726 (note to Foshag), $2V=72°$ (calcd.), dispersion strong, $r>v$. Fluoresces an intense blue under ultraviolet excitation, shows sharp luminescence bands and a diffuse band under cathode-ray bombardment. These are attributed to trivalent rare earths and bivalent europium.

Occurrence: In grains and in lamellar masses 1 mm. thick in nepheline dikes with associated phlogopite and plagioclase. The dikes cut limestone in the Johachido district, Kenkyohokudo Prefecture, Korea.

Discussion: The specific gravity and indices of refraction are astonishingly high for a mineral of this composition. Presumably the structure must be one of very close packing.

Michael Fleischer

Nigerite

R. Jacobson and J. S. Webb, The occurrence of nigerite, a new tin mineral in quartz-sillimanite-rocks from Nigeria. *Mineralog. Mag.*, **28,** 118–128 (1947).

F. A. Bannister, M. H. Hey and H. P. Stadler. Nigerite, a new tin mineral. *Mineralog. Mag.*, **28,** 129–136 (1947).

Crystallography: Hexagonal, rhombohedral, occurring as hexagonal plates up to 5×2 mm. in size, but mostly smaller. All crystals examined had a brilliantly reflecting basal plane. Other forms observed include $(10\bar{1}1)$, $(10\bar{1}3)$ and a doubtful form $(3.0.\bar{3}.16)$. Rotation photographs gave $a=5.71$, $c=13.83$ kX. Six space groups are possible, but as tests for piezoelectricity were negative, perhaps only the non-polar groups $C\,\bar{3}\,m$ or $C\,\bar{3}1\,m$ need be considered. The structure is hexagonal close-packed, as shown also by oriented overgrowths with (0001) of nigerite on (111) of gahnite. *X*-ray powder data are given.

Chemical properties: Analysis by Hey of a 2 g. sample that contained very little quartz and sillimanite gave PbO 0.94, MnO 0.09, FeO 2.65, ZnO 4.51, SnO_2 25.33, TiO_2 0.17, MgO 1.28, Fe_2O_3 11.90, Al_2O_3 50.91, H_2O 1.57, SiO_2 0.48; sum 99.83%. Spectrographic traces of Li and P were found in some samples. The H_2O is very firmly held, 0.11% is lost at 200°, 0.38% at 900°C. The analysis gives $(Zn, Mg, Fe'')\,(Sn, Zn)_2(Al, Fe''')_{12}O_{22}(OH)_2$.

Nigerite is insoluble in acids, imperfectly attacked by fusion with Na_2CO_3 or NaOH, readily gives clear fusions with borax and $Na_2S_2O_7$.

Physical and optical properties: Color dark brown. Density (corrected for quartz) $D_4^{16}=4.51$. Hardness between 8 and 9, brittle. Weakly magnetic. Optically positive, approximate indices of refraction $nO=1.80$, $nE=1.81$.

Occurrence: Nigerite occurs at four localities in the Egbe district, Kabba province, central Nigeria. It occurs in quartz-sillimanite rocks closely associated with cassiterite-bearing granitic pegmatites. Associated minerals are quartz, sillimanite, andalusite, muscovite, gahnite, garnet, cassiterite, columbite-tantalite, chrysoberyl, and apatite.

M.F.

Eulite

Arie Poldervaart, The relationship of orthopyroxene to pigeonite. *Mineralog. Mag.* **28,** 164–172 (1947).

The following new nomenclature, analogous to those used for the plagioclase and olivine series, is proposed for the orthorhombic pyroxenes (enstatite (En)—orthoferrosilite (Of) series).

Enstatite —100–90% $MgSiO_3$
Bronzite —90–70
Hypersthene —70–50
Ferrohypersthene—50–30
Eulite —30–10
Orthoferrosilite —10–0

The name eulite is suggested, since the pyroxenes of this composition range occur mainly in eulysite rocks.

Discussion: If six names must be used, the proposed classification is logical, but is it not easier to use the single name orthopyroxene with the composition? Thus, in place of eulite, one can write orthopyroxene (En_{20}) or orthopyroxene ($En_{20}Of_{80}$).

M.F.

NEW DATA

Skutterudite Series

Ralph Jerome Holmes, Higher mineral arsenides of cobalt, nickel, and iron. *Bull. Geol. Soc. America*, **58,** 299–392 (1947).

This paper gives the results of a detailed and thorough study of both natural and artificial materials. Microscopic, *x*-ray, contact-print, and mineral synthesis techniques were used, and a critical review of the nearly 200 recorded analyses is given. The results show that some changes are necessary in the present nomenclature of these minerals.

The supposed isometric biarsenides, RAs_2, are shown to be structurally identical with the isometric tiarsenides, RAs_3, in agreement with the work of Oftedal and Peacock. This raises the question of what names to use. *Dana's System of Mineralogy*, 7th Ed., Vol. I, while recognizing the structural identity, retains the names smaltite (Co dominant), chloanthite (Ni dominant), and chathamite (Fe dominant) to designate varieties of the isometric arsenides which have ratios R: As of 2.0 to 2.5. Holmes states, "The application of special names to varieties whose analyses exhibit deviations in arsenic ratio from the theoretical composition RAs_3 is unnecessary since in many cases this is due to mechanical inhomogeneity. Structurally they are all triarsenides of the skutterudite type, even though the arsenic deficiency may in some cases be due in part to substitution of metal for arsenic." Holmes therefore names the skutterudite series by three names only, for the members with Co, Ni, and Fe dominant. I agree with this proposal, except that it is doubtful that a name is needed for RAs_3 with Fe dominant. No analyzed minerals correspond to the theoretical end-members $NiAs_3$ and $FeAs_3$; the existence of RAs_3 with Ni dominant is clearly established, but the evidence for a mineral RAs_3 with Fe dominant is unsatisfactory.

The following names have been used in the past for these isometric arsenides: for Co dominant, skutterudite (triarsenide) and smaltite (supposedly a biarsenide); for Ni dominant, nickel-skutterudite (triarsenide) and chloanthite (supposedly a biarsenide); for Fe dominant, iron-skutterudite (triarsenide) and chathamite and arsenoferrite (both supposedly biarsenides). Holmes now discards all these names except skutterudite and proposes the names nickelian skutterudite and ferrian skutterudite for the triarsenides (RAs_3) with Ni and Fe, respectively, dominant. These names are inadmissible. The uniform adjectival modifiers were proposed by Schaller to express "a minor and variable isomorphous replacement of an essential chemical element of a mineral by another analogous element." Their use as mineral names, as suggested by Holmes, is a radical and confusing change in the usage proposed by Schaller, adopted by the Mineralogical Society of America, and used in the 7th Edition of *Dana's System of Mineralogy.* Holmes in places also uses them correctly, as, for example, cobaltian loellingite. This use of the adjectival modifiers to mean two different things is very bad, as such a scheme can be useful only if unambiguous. Furthermore, restricting the use of the adjectival modifiers to that now generally accepted makes Holmes' terms (cobaltian) skutterudite and (ferrian) loellingite unnecessary and redundant.

For the Co-dominant mineral, the well-established name skutterudite is clearly to be preferred, and the name smaltite should be discarded, as proposed by Holmes. He also shows that the material called chathamite is orthorhombic and that the name should not be used for the isometric mineral. This leaves a choice between nickel-skutterudite and chloanthite for the Ni-dominant mineral, and between iron-skutterudite and arsenoferrite and no name at all for the Fe-dominant mineral. The choice is difficult, as there are objections of all the possibilities.

Holmes objects to the retention of chloanthite as the name for the isometric triarsenide because it has long been applied to the supposed biarsenide. Although this could lead to some confusion, hyphenated compound mineral names like nickel-skutterudite are so undesirable because of their ambiguity that it seems best to use the name chloanthite for the isometric triarsenide with Ni dominant. No name is needed for the isometric triarsenide with Fe dominant until clear evidence of its existence is brought forward.

M.F.

DISCREDITED MINERALS

Custerite (=Cuspidine)

C. E. Tilley, Cuspidine from dolomite contact skarns, Broadford, Skye. *Mineralog. Mag.*, **28,** 90–95 (1947).

Custerite from Custer County, Idaho (type locality), and cuspidine from two localities had nearly identical optical properties and gave identical *x*-ray powder patterns. The formula for custerite, $Ca_4Si_2O_7(F, OH)_2 \cdot H_2O$ differs from that of cuspidine only in having an additional H_2O. The minerals are undoubtedly identical, although the Idaho material may have a lower F:OH ratio, and the name custerite should be discarded.

M.F.

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